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AN OPEN-LOOP TRANSIENT THERMODYNAMIC
## MODEL OF THE COUGUAR TURBOJET(U)

by

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SUMMARY

An open-loop, transient, thermodynamic model of the single-spool Couguar turbojet has been developed for use in both fault diagnosis and engine control research work. The model is based on *TURBOTRANS*, a generic engine modelling computer program, and it has been calibrated against test cell measurements of the steady-state running line. The model provided good predictions of a series of accelerations and decelerations over the operating range of the turbojet. Estimates of the steady-state gains and time constants, across the speed range of the engine, are also presented.

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NOMENCLATURE

BD	brick data
DP	design point cycle
E	error variable in ODP solution procedure
EB	base value of error variable
EV	engine vector
FN	net thrust
I	spool moment of inertia
ISA	international standard atmosphere
MA	air flow
N	spool speed
ODP	off-design point cycle
P	total pressure
PR	compressor pressure ratio
PLA	power lever angle
SV	station vector
T	total temperature
TF	turbine flow function
TWF	fuel temperature
V	independent variable in ODP solution procedure
VB	base value of independent variable
WF	fuel flow
Z	distance along the constant speed line of a compressor characterisitc (from surge line)
Δ	change in
η	compressor efficiency
σ	standard deviation

Subscripts

c	corrected to ISA and sea-level static conditions
cgr	Couguar turbojet
Des	design point value
i,j	variable indices
ref	reference value
s	static
t	value at end of transient (16.0 seconds)

Station Locations

0	ambient conditions
1	intake inlet
2	compressor inlet
3	compressor outlet
4	turbine inlet
5	turbine outlet
7	jet pipe inlet
8	nozzle inlet
9	nozzle outlet

1. INTRODUCTION

A single-spool Microturbo Couguar turbojet engine has been installed in the Small Engines Test House (SETH) for use as an experimental research rig. It is a small, simple turbojet engine which produces a design thrust of 176 lbs, at a spool speed of 48,500 rpm and an air mass flow of 3.4 lb/s. Originally, the engine operated in the Turana target drone.

Currently, the Couguar turbojet test rig is being used to evaluate the methodology being developed in two ARL tasks. The first task, Gas Turbine Transient Research, involves the development of fault diagnostic techniques which can be applied to transient engine data. The second task, Engine Control Systems, involves the development of methodology for the analysis, design and fault diagnosis of digital gas turbine engine control systems. In both these tasks, there was a requirement for a transient, thermodynamic model of the Couguar turbojet and the objective of this work was to provide such a model.

The computer program TURBOTRANS, which was developed at Cranfield Institute of Technology, has been used for the engine modelling work; it is a generic, transient, component based, thermodynamic engine model. The current work involved configuring the TURBOTRANS program to the specific geometry of the Couguar turbojet, and validating the model simulations against experimental data. Data were obtained in a complementary experimental investigation which, firstly, measured the steady-state running line of the turbojet and, secondly, measured a series of accelerations and decelerations across the operating range of the turbojet.

One objective of the controls research is to develop a digital closed loop controller for the turbojet. This requires the development of a real time transfer function model of the turbojet, which in turn requires the steady-state gains and time constants of some of the thermodynamic parameters to be determined. Therefore, the transient model was used to estimate the time constants of the engine parameter responses to small step changes in fuel input.

In the following sections, the implementation and validation of an open-loop, transient, thermodynamic, computer model of the Couguar turbojet is described and the steady-state gains and time constants of the turbojet are presented.

2. ENGINE TEST RIG

2.1 Description of test rig

The Couguar engine test rig installed in the SETH can be divided into the following components the Drone Activation and Monitoring Equipment (DAME), the Engine Test Stand (ETS), the Couguar turbojet, the Data Aquistion System and the instrumentation; these components are described below. The DAME and ETS are equipment used in the ground and pre-flight operation of the Turana Target Drone. A photograph of the Couguar turbojet mounted in the test stand is shown in Fig 1.

2.1.1 Drone Activation and Monitoring Equipment

The engine starting and running is controlled from the Drone Activiation and Monitoring Equipment. T.is comprises five sub-units bolted together; the units are as follows: the sequence and monitor panel, the engine starting panel, the fuel control unit, the starting air unit and the drone external power supply. The DAME is located in the engine cell but the engine is operated from the control room. To facilitate this the throttle knob and the following instruments, throttle demand voltage, engine spill valve actuating current and engine speed, were removed from the engine starting panel and placed in the control room panel. The appropriate electrical connections were made between the two panels.

A new and different throttle was installed in the control panel; it was a horizontal sliding knob with its position marked by a vernier scale. For a given transient, the upper and lower limits of throttle travel could be set by adjustable stoppers; this enabled accurate and repeatable start and end points to the throttle movements.

2.1.2 Engine Test Stand

The Engine Test Stand (ETS) was designed for ground testing of the engine, in particular, for those tests that cannot be carried out in the target drone. As such, all air and electrical connections between the DAME and the ETS are made by the same air and electrical umbilicals as those used for the drone. However, it was not appropriate to use the fuel system located in the ETS, which is similar to that of the

drone. Instead, the engine has been connected directly to the testcell fuel tank to allow prolonged running of the engine.

The engine is mounted on a floating table, by means of flexured pivots and this enables the test stand to be used for engine thrust measurements. A load cell has been mounted on the main frame of the ETS.

2.1.3 Engine Configuration

The simple configuration of the single-spool Couguar turbojet is shown in Figure 2. The single entry air intake, of the target drone is not used in the testcell. Instead, a cylindrical bellmouth attachment - which is calibrated for air mass flow measurements - encloses the central nose bullet. The gas generator section comprises a single stage centrifugal compressor, an annular reverse flow combustor and a single stage axial flow turbine. The exhaust is a jet pipe with convergent nozzle. The engine control system is a simple closed loop speed governor without any compensation for inlet pressure or temperature.

2.1.4 Data Acquisition System

The Data Acquistion System is built around a DEC LSI-11/73 computer and the DAOS software package (copyright) which has been developed by Laboratory Software Associates of Melbourne. DAOS is an interactive programming language expecially designed for computer based data acquisition systems. The configuration used for the Couguar tests involved 28 signal channels recording data at 32 Hz and in blocks of 16 seconds i.e. 512 readings per channel per block read. 20 Channels (0-19) were set up to measure analogue signals, i.e. parameters taken as proportional to the voltage measured. 8 Channels (20-27) were set up to measure pulse rate signals, i.e. parameters taken as proportional to the frequency measured. The parameters allocated to each channel are listed in Appendix A.

An oscillograph provided the means for a real time display of 8 parameter signals. The raw data are stored on a Winchester Disk during the runs and afterwards are copied to floppy disks for archive. Duplicate copies are made. The raw signal data are converted to engineering units on the DEC LSI-11/73 and these data can be graphically displayed on the VDU in the control room at the end of each individual test. As the engine computer models are implemented on the ELXSI mainframe

computer the test cell data needed to be transferred across. This posed a problem as the format of the data values stored on the DEC LSI-11/73 disks, could not be read by the ELXSI and an intermediate step was required. The EDS VAX – 750 computer provided the conversion between the LSI -11/73 binary format and the ANSII format readable by the ELXSI.

2.1.5 Instrumentation

The pressure and temperature instrumentation were placed at the station locations 2, 3, 4 and 5 as shown in Fig 2. Rosemount pressure tranducers were used for the absolute pressure measurements and type K thermocouples were used for the temperature measurements. At each station, the pressure and temperature probes were placed at three points around the circumference of the engine. The pressure difference across the bellmouth intake – as required for calculating the engine airflow – was measured by a Setra differential pressure transducer.

There were problems with the accuracy of the temperature measurements at the combustor outlet, station 4, and the turbine outlet, station 5. An earlier ARL study (1) found the circumferential temperature distribution at the combuster to be non-uniform as a result of internal obstructions to the airflow. The magnitude of the temperature varied about the mean value by up to 15% with two peaks some 180° apart and two troughs some 180° apart. Although of reduced magnitude, this maldistribution persisted through to the jet pipe. Consequently, more thermocouples than the three used are required for an accurate mean temperature measurement and so a bias in the T4, T5 readings was to be expected. Furthermore, the accuracy of T4 was suspect as one of the T4 thermocouples was open circuit.

Generally, the parameter signals were not noisy. However, the fuel flow signal was the exception; it was noisy, and, on average, the 2 σ bands about the mean signal were ± 3.55% Ideally, for the model validation work, the fuel flow signal should have had the lowest noise. This is because, in simulating open-loop transients, an appropriately smoothed fuel-time trace is the primary input parameter to the model. Consequently, uncertainty in the smoothed fuel flow value leads to uncertainty in the correctness of the match between the simulated and experimental transients. A reduction in the noise of the fuel flow signal is one area where the instrumentation should be improved for future transient work.

2.2   Experimental Program

The two main tasks of the experimental program were:

a.   to measure the steady-state running line of the Couguar turbojet; and

b.   to measure a number of representative engine accelerations and decelerations across the operating range of the turbojet.

The running line data were used to calibrate the steady-state, off-design, portion of the engine model and the transient data were used to validate the simulations of the transient model.

The running line of the engine, with a standard area nozzle, had been established during a recent ARL investigation into the effect of different area nozzles on the performance of the Couguar turbojet. As the engine had not been run during the intervening period i.e. no difference due to degradation was expected, and as the running line was a simple monotonic curve i.e. a small number of points required for definition; it was not considered necessary to obtain a comprehensive set of steady-state data to re-establish the running line.

The steady-state readings were recorded between the various transient tests, both before and after each transient and, consequently, at one of the six throttle positions used in the transient tests. These readings were taken when at least 3 minutes had elapsed from the previous throttle movement.

Four throttle ranges were used in the transient tests. The lower and upper throttle position of each range were, respectively:

a. 70° and 100° PLA i.e. 91 and 101 % N_{Des};

b. 50° and 100° PLA i.e. 82 and 101 % N_{Des};

c. 60° and 80° PLA i.e. 86 and 96 % N_{Des}; and

d. 20° and 70° PLA i.e. 68 and 91 % N_{Des}.

For each throttle range, the program involved doing firstly an acceleration and secondly a deceleration. These two tests were then repeated before going onto the next throttle range.

The acceleration and decelerations were first done as slams i.e. bursts and chops. Having done this for all four ranges the tests were then repeated but the throttle was moved as evenly as possible, to completion, over a two second interval, i.e. a ramp acceleration or deceleration.

Overall, the test program involved 70 individual recordings. Of these, 38 were steady-state records and 32 were transient records.

3. ENGINE MODEL

3.1 Description of Generic Model

The generic, transient, component based, thermodynamic engine modelling code TURBOTRANS has been used to model the Couguar turbojet. TURBOTRANS has evolved from a number of earlier steady-state codes that were developed at the Cranfield Institute of Technology. However, the equations for the transient update are taken directly from the NASA transient code DYNGEN (2). The advantage of TURBOTRANS over DYNGEN is that the Brick-Codeword concept for inputing arbitrary engine configurations via a datafile has been extended to cover control configurations. In contrast, DYNGEN requires a new subroutine to be written each time the controller configuration is changed.

The users' guide for TURBOTRANS (3) shows how to operate the program and how to model various engine geometries. Furthermore, an overview of the methodology and capabilities of TURBOTRANS is given in (4). However, a more detailed description is required if one is to change the source program. This information can be found in (5) where the equations and structure of the steady-state portion of the model are detailed and in (2) where the transient equations are detailed. The main features of the TURBOTRANS code are summarized below.

3.1.1 Brick Concept and Codewords

TURBOTRANS is a flexible engine code; it can model arbitrary gas turbines with arbitrary control systems without the need to rewrite and recompile sections of the computer program. This is achieved through the use of the Brick concept and Codewords.

The Brick concept reduces the many possible engine configurations to the few basic thermodynamic processes such as compression, expansion, combustion, duct flow, etc, which govern engine operation. A separate Thermodynamic Brick is formed for each process. The process may also correspond to a specific engine component eg. expansion – turbine. Similarly, the control system is reduced to the governing processes such as, sensor lag, feedback, transfer functions, etc. A particular engine configuration can then be built up by using a number of suitable Thermodynamic Bricks and Control Bricks. In TURBOTRANS, there are 14 Thermodynamic Bricks and 12 Control Bricks available to configure the engine.

The linking of the individual Thermodynamic Bricks is facilitated by the use of a standard, but redundant set, of eight parameters to specify the gas state at the inlet(s) and outlet(s) to the Brick. The parameters are as follows:

a. fuel/air mass ratio;
b. gas mass flow;
c. static pressure;
d. total pressure;
e. static temperature;
f. total temperature;
g. velocity; and
h. area.

Collectively, they are called the Station Vector (SV). However, to completely specify the action of the brick, additional information is usually required and this is entered via one of two data vectors, either the Brick Data (BD) or the Engine Vector (EV). The Brick Data contains the parameters which are required for Brick calculations. The Engine Vector contains the parameters which are calculated by the Brick. The Engine Vector data may or may not be used in subsequent Bricks.

The engine configuration is entered through the input data file by specifying an appropriate sequence of Codewords. Each Codeword consists of a brickname followed by one or more descriptors. The descriptors specify the stations between which the Brick is operating and the vector address number of the Brick Data, Engine Vector results and Variables which are required by the Brick. The codewords are decoded by the subroutines BRKNAM and BRKDES, which seek and recognize, respectively, the brickname and descriptor characters as they are being read from the input datafile. The Bricks are automatically linked and executed in the order that is specified by the Codewords.

There are basically two types of calculations in the component Bricks. The first involves entering and searching component characteristic maps to determine the specific component performance. The second involves solving the general thermodynamic equations which govern the component process. Importantly, it is the component maps – given the same engine configuration – which distinguish the performance of one engine from another.

3.1.2   Component Maps

In TURBOTRANS, four types of maps are used, compressor, combustion chamber, turbine and nozzle coefficient. Whilst the program uses only one combustion chamber map and one nozzle coefficient map, there are five compressor maps and five turbine maps to choose from. However, only two of the five maps are unique; the other three maps are scaled versions of these two. Furthermore, the user can read in other compressor and turbine maps via the input datafile.

Maps of similar shape but different magnitude can be used as TURBOTRANS has an automatic map scaling facility. The map scale factors are calculated once during the design point case. The scale factors are simply the ratio of desired design point values of the component performance parameters, as specified in the Brick Data, to the actual parameter values read from the component map given the design point values of the input parameters.

Each component map has two input parameters which are used to read the values of the performance parameters from the map. There are one to three performance parameters depending on the map. For the compressor map, the inlet parameters are corrected spool speed (N_c) and the distance along a constant speed line of a compressor characteristic map (Z); and the performance parameters, which

are read from the map, are pressure ratio (PR), compressor efficiency (η), and corrected mass flow (MA_c). These performance parameters are then scaled to match the design conditions. The same set of scale factors is then used to scale the maps for all the subsequent off-design cases.

3.1.3   Off-Design Solution Procedure

The engine components are matched in the off-design cycle (ODP) calculations, hence the engine is balanced, by satisfying the following constraints:

    a.   the mass flow continuity;

    b.   the rotational speed balance on each shaft;

    c.   the power balance between each compressor and turbine on the same shaft;

    d.   the pressure balance across the exhaust nozzle; and

    e.   the static pressure balance for each mixing process (turbofans).

TURBOTRANS, like other engine codes, uses the Newton-Raphson iteration method (5) to solve for the steady-state operating point which satisfies the above matching constraints.

To describe the ODP solution procedure the following terms need to be defined, the ODP condition data, an Error and a Variable.

The ODP condition data are those Station Vector and/or Brick Data parameters chosen to define the ODP operating conditions. Typically, for a single spool engine, the steady-state running line is generated by specifying one of the following, the spool speed (N_c), the fuel flow (WF) or the turbine inlet temperature (T_4). There are two restrictions on the choice of the ODP parameter; it cannot be a performance parameter read from a component map e.g. PR or η or MA_c; it cannot be previously specified as a Variable in a Brick Codeword.

Error variables are formed from the matching constraints. Importantly, the calculation procedure is redundant and therefore matching parameters such as continuity, turbine power and nozzle pressure can be calculated in more than one way. This leads to the formation of an Error variable. The Error variable is the difference between the value of the matching parameter which is calculated from the component inlet conditions and the value which is obtained from the component

map. Initially, in the ODP calculations the matching constraints will not be met and the magnitude of the Errors will represent how much the engine is out of balance. In a single spool engine three Errors are calculated; the continuity and power imbalance in the Turbine Brick and the pressure imbalance in the Nozzle Brick.

The Variables are those BD or SV parameters which are designated the independent variables in the Newton-Raphson technique. These are the parameters which are altered until the engine balances, i.e. until the errors approach some acceptable tolerance. The Variables chosen are specified in the appropriate Brick Codeword. They may be any BD or SV parameter, but they are usually selected from the following:

a.   shaft rotational speed N_c;
b.   distance along the constant speed line of a compressor characteristic map Z;
c.   turbine inlet temperature T_4;
d.   bypass ratio; and
e.   turbine flow function parameter TF.

In a single spool engine, there are three Error variables and so three independent Variables are required. If the ODP condition is specified by N_c then Z, T_4 and TF would be an appropriate choice of Variables.

The Newton-Raphson technique assumes the Errors E to be some function of the Variables V and solves a set of partial differential equations for this function to obtain the Variable values V_j which balance the engine. The partial differential equations are of the form

$$dE_i = \sum_{j=1}^{n} \frac{\partial E_i}{\partial V_j} \; dV_j \qquad \begin{array}{l} i = 1,2\ldots n \\ j = 1,2\ldots n \end{array} \qquad (1)$$

where n is the number of Errors for a particular engine configuration. The changes in the Variables are assumed to be small and the following approximations are made

$$dE_i = E_i - EB_i \qquad (2)$$

$$dV_j = V_j - VB_j \qquad (3)$$

where VB_j is the arbitrary base value of V_j and EB_i is the ith base error due to all VB_j values. The set of simultaneous linear equations which are to be solved for dV_j are obtained by substituting equation (2) into (1) and by taking the Errors equal to zero, $E_i = 0$, for a balanced engine. These equations are solved by conventional matrix methods. The new values of V_j are then obtained from equation (3). In general, the engine is a non linear system and so the engine will not be balanced by the first set of V_j values. Consequently, the procedure is repeated iteratively until the engine is balanced. In the subsequent iterations the new values of V_j are used as the VB_j values.

In TURBOTRANS, the crux of the Newton-Raphson technique is the calculation of the partial derivatives $\partial E_i / \partial V_j$. These represent the change in Error E_i caused by a change in Variable V_j. The partial derivatives are calculated in the following manner. The ODP conditions are input. The program then does a run through the engine with all the variables V_j at their DP values. These are the initial base Variable VB_j values. Naturally, the engine is not balanced and the resultant Error values are designated the base errors EB_i. The program then increments the first Variable V_1 and repeats the engine run. The resultant Errors due to the out of balance are designated the Error partial derivatives with respect to V_1. V_1 is then reset to its initial value and the second Variable V_2 is incremented and the Errors for this Variable calculated. This procedure is repeated until the number of Variables changed is equal to the number of Errors for the particular engine configuration. In this way, the matrix of partial derivatives is built up. In the case of a single-spool turbojet, nine partial derivatives need to be calculated as there are three Errors and three Variables.

3.1.4 Transient Model

The transient model is a straight forward extension of the steady-state model. Only, three types of equations, the continuity, energy and power balance are modified to include the engine dynamic terms. Importantly, the transient update does not change the ODP iteration scheme.

In unsteady flow, there is mass and energy storage and so the steady-state continuity and energy equations need to be adjusted for this storage. To do this, a control volume has been associated with each component. In the continuity equation, *a single term is added. It accounts for the rate at which mass is stored in the*

component volume; it is taken to be proportional to the component volume times the time derivative of pressure. In the energy equation, two terms are added. The first is for the rate of change of specific internal energy; the second is for the energy storage caused by mass storage.

In unsteady flow, any excess power produced by the turbine goes into rotor acceleration. Therefore, the power balance is modified by adding a rotor acceleration term. It is proportional to the rotor moment of inertia times the time derivative of spool speed.

The time derivatives in these equations are not solved for explicitly but rather iteratively by the modified Euler method (2). The simplest possible approximation is used for the time derivative. It is taken equal to the current value of the parameter minus the parameter value for the previous time step divided by the time step. As the Newton-Raphson technique is also iterative, the solution of the time derivative is simply embedded in the overall ODP solution procedure.

The modified Euler method is fairly robust and does not require extremely small time steps to obtain a stable solution. Typical time steps are in the range 0.001 to 0.1 seconds.

3.2 Implementation of Program

3.2.1 Input Datafile

To operate TURBOTRANS, as a model of the Couguar turbojet, the main task, for the user, is to form an appropriate input datafile. The method of doing this is described in the Users' Guide (3). It is through the input datafile that the following are specified:

a. the type of calculation whether DP or ODP, steady-state or transient, etc.;

b. the component data maps and control schedules;

c. the engine and control configuration;

d. the BD and SV values for the DP condition, and

e. the BD and SV values for the ODP conditions.

A cipher for the input datafile has been formed and it is listed in Appendix B-1. It briefly summarises and describes the various terms required for the open-loop transient model of the Couguar turbojet.

3.2.2 Modes of Operation

In this study, the program was operated in the following three modes:
- a. as a steady-state, off-design point cycle calculation to simulate the steady-state running line of the engine;
- b. as an open-loop, transient, off-design point cycle calculation to simulate accelerations and decelerations of the engine; and
- c. as a fuel-step, transient, off-design point cycle calculation to estimate the time constants of the engine.

The input datafile required for each mode is discussed below. However, before this is done the changes made to the source code and the calculation of component data are discussed.

3.2.3 Source Code Changes

There was a need to upgrade the output routines to provide better presentation of the results, including new tabulation formats and graphics. In TURBOTRANS, the results for a given operating condition are printed out once the convergence criteria have been satisfied, but they are not stored in vector arrays. Consequently, these results are overwritten by the next set of calculations and cannot be recalled for future use. Furthermore, not all calculated parameters are listed and the format of the output listing is not the most convenient for extracting parameter values from. For the above reasons, two subroutines were written, subroutine MAKEVEC to store all calculated parameter values at the completion of a cycle calculation and subroutine VECOUT to printout all vector arrays at the completion of the program run. This output file is then used as the input file for the post-processing programs which tabulate and plot the results.

The program was also modified to account for the effect of sensor lag on the transient response of measured temperatures. That is, the gas temperatures predicted by TURBOTRANS are lagged to give the measured temperatures. To do this, a new subroutine called LAGOUT was written. It is based on the existing TURBOTRANS algorithms which are used in closed-loop control to model the first-

order lag of control signal sensors. To match the measured temperature response a one second time constant was found to be appropriate.

3.2.4 Couguar Component Data

Apart from the actual engine configuration, the specific performance of the Couguar turbojet is established via individual component maps and design point values of the component parameters. However, a component based model does pose some problems to the user. Firstly, component maps are treated as proprietary information and are very difficult to obtain. Secondly, adequate component maps are difficult to generate from engine measurements. This is because the range of component operation is restricted to the engine running line values by overall matching constraints and control schedules.

For the Couguar, only the compressor map was available. Generic maps had to be used for the turbine, combustor and nozzle coefficient maps. These were appropriately scaled by the specified design point values. Two earlier ARL investigations into the in-flight performance of the Couguar Combustor (6, 7) did provide a means of checking that the calculated values of combustion efficiency and air/fuel ratios were appropriate.

The values of the dynamic input parameters, the component volumes and the spool moment of inertia, are shown in Appendix B-2. These were calculated from the respective measurements of the component flowpaths and the compressor/turbine rotor dimensions.

3.2.5 Off-Design Steady-State Operation

The input datafile used to generate the Couguar steady-state running line is shown in Appendix B-3. Here, the ODP condition is specified by N_c - expressed as a fraction of N_{Des} - and the chosen Variables are Z, T4 and TF. Alternatively, one may use WF or T4 to specify the off-design condition and Z, N_c and TF as the required Variables.

As WF is used in the transient case, it was important to check that the steady-state ODP values calculated with WF did accurately reproduce the ODP values calculated with N_c. In other words, the steady-state predictions of the model should be independent of the parameter used to specify the ODP condition. Whilst a series

of simulations showed this to be generally so, two problems did emerge. Firstly, for WF the ODP cycle calculations failed to converge if the fuel flow step from the previous ODP value was too large. For example, a running line could not be generated by using the fuel flow values corresponding to 5% changes in N_c. Secondly, for spool speeds less than 65% N_{Des} the corresponding WF values did not calculate the correct conditions but rather converged on a spool speed of 25% N_{Des}. The causes of these convergence problems, which could have been related to the non-linear iteration scheme, were not determined. However, they were not encountered in the transient simulations.

3.2.6   Open–loop Transient Operation

The input datafile used to generate a typical open-loop Couguar transient is shown in Appendix B-4. Reference has already been made to Appendix B-1 which describes the various terms appearing in the datafile. It should be pointed out that the standard TURBOTRANS input format is not set up to model transients with open-loop control but rather transients with closed-loop control. However, the standard format can be adapted to specify the open-loop model.

In closed loop control, the control schedule is specified by inputing a power lever angle PLA versus time trace together with up to four other parameter schedules expressed as a function of PLA. In contrast, for open-loop control, only a fuel flow versus time trace is required to specify the ODP condition. This has been done by, simply, inputing a psuedo PLA versus time trace where the PLA is some multiple (1000 times here) of the desired fuel flow value. The WF versus PLA schedule then ensures the correct WF value is used in the calculations. Clearly, the value of the pseudo PLA does not equal the actual engine PLA.

The measured fuel flow signal is not used as the input fuel flow time trace but rather a smoothed estimate of the measured signal is used. This is because TURBOTRANS cannot handle noisy input data; it is a deterministic model. The smoothing involved averaging the 512 fuel flow readings (16s at 32Hz) in the trace over various time intervals. In the quasi steady-state portions of the trace large time intervals or periods were used. In the transient portion of the trace, where the slope changes more rapidly, smaller periods were used. In total, 30 points were used to define the input trace. To do this the dimensions of the input control schedule vectors were increased from the original 10 points to 30.

A psuedo Main Fuel Control Unit has also been specified in the datafile. It performs the function of transferring the input fuel flow value from the control schedule data vector to the appropriate location of the fuel flow in the Brick Data vector. It is this latter value which is used in the ODP cycle calculation.

To model different accelerations or decelerations only three changes need to be made to the input datafile. Firstly, the time and psuedo PLA values are changed to input the new fuel flow-time trace. Secondly, the value of the fuel flow at time zero is also specified in ODP condition data - location BD (19). Thirdly, the measured inlet temperature of the given experimental run is specified in the ODP condition data. The other parameters such as the design point Station Vector and Brick Data values have been set by the calibration of the model against the steady-state running line, and naturally, the calculated values of the spool moment of inertia and component volumes remain fixed.

3.2.7 Fuel-Step Transient Operation

There is an option in TURBOTRANS, which models fuel-step transients from time zero. This option is specified through the design point Brick Data values. However, as it was required to initiate the fuel step at a finite time the open-loop format of the input datafile has been used to specify the fuel-step transient. In addition, a program TURBORAWFSDAT has been written which reads the resultant output from TURBOTRANS and calculates the various parameter time constants and steady-state gains from the simulated response of the parameters to the fuel-step input.

4. RESULTS AND DISCUSSION

4.1 Steady-State Running Line.

4.1.1 Experimental Data

The steady-state operating points were calculated by averaging the parameter readings (128) over the last four seconds of the 16 second record. Also the parameter signal noise was estimated by calculating the standard deviation σ associated with each parameter mean. The parameter 2σ values for all operating points were then averaged to give the signal noise estimate. The resultant values are given in Table 1. Apart from the fuel flow signal, the noise on the

parameter signals is low. The problems associated with high fuel flow signal noise
have been discussed previously in section 2.1.5.

TABLE 1
PARAMETER SIGNAL NOISE

($\pm 2\,\sigma$ bands expressed as a % of the Parameter value at 100% N_{Des})

Parameter	N	MA	P3	T3	WF	P4	T4	P5	T5	FN
$\pm 2\,\sigma$ band	0.36%	0.79%	0.40%	0.14%	3.55%	0.36%	0.28%	0.74%	0.22%	0.33%

The steady-state operating points which were measured before and after each
transient test were found to lie on the previously determined steady-state running
line. The values of the major parameters of interest are given in Table 2 for 5%
speed increments across the operating range of the turbojet. These parameter values
have been corrected to International Standard Atmosphere (ISA) and Sea-level Inlet
Conditions.

4.1.2 Model Calibration

The calibration of the engine model against the experimental steady-state
running line involved a series of simulations using different combinations of design
point parameter values and component efficiencies. These parametric studies
determined, firstly, the combination of input data which gave the best match and
secondly, the sensitivity of the simulation to the various input data.

A listing of the input data file for the best simulation of the running line is given
in Appendix B-3. The inlet conditions were ISA and Sea-level. The final match
between the simulated and experimental running line is shown in Figures 3A, 3B and
3C. Also the simulated results for 5% speed increments are given in Table 3 and a
direct comparison can be made with the experimental values given in Table 2. The
percentage difference between the simulated and experimental running line data, at

each 5% speed interval, has also been calculated and the resultant differences are tabulated in Appendix C-1. Overall, the final match between the simulated and experimental running line is good. However, in generating the match there were two areas where the simulation appeared deficient and these are discussed below.

On average the simulated T4 values are 40K (4% of $T4_{Des}$.) above the measured T4 running line. Whilst a match could be obtained by reducing the design combustion efficiency to 80%; this was not an appropriate value to use. An earlier ARL study (7) had measured Combustor efficiencies of between 90% at $60\%N_{Des}$ and 96% at $100\%N_{Des}$. Furthermore, as discussed previously in Section 2.1, the accuracy of the T4 reading is questionable and a negative bias of 40K would not be unexpected. Therefore, the simulated T4 values have been accepted as reasonable.

The simulations of P3, P4, FN and WF progressively diverge from the experimental running line as the speed is reduced from 70% to 60% N_{Des}. In fact, the divergence in the initial simulations began at 80% N_{Des} and were very large by 60% N_{Des}. To improve the match in this region the Compressor Component Map had to be changed. Changes to the design point parameter and efficiency values could not effect a change in the shape of the running line. The two speed lines labelled as 35000 and 29200 RPM on ARL's copy of the manufacturer's compressor characteristic were changed to 33000 and 27200 RPM, respectively, whilst the corresponding pressure ratio, mass flow and efficiency values remained the same. Given the agreement obtained from using these changes in engine speed, there is some justification for concluding that the speed lines on the component map had been wrongly identified. Clearly, further improvement in the match could be obtained from more changes to the Compressor Component Map in the 60 to $70\%N_{Des}$ region. However, this was not pursued. The small divergence was considered acceptable given that the operating range of primary interest was from 80 to 100% N_{Des}.

TABLE 2

EXPERIMENTAL STEADY-STATE RUNNING LINE

(Corrected to ISA and Sea Level Static Conditions)

$\frac{N_c}{N_{Des}}$ % of Des	MA_c lb/s	$\frac{P3}{P0}$	$\frac{T3}{T0}$	WF_c lb/s	$\frac{P4}{P0}$	$\frac{T4}{T0}$	$\frac{P5}{P0}$	$\frac{T5}{T0}$	FN_c lbf
100.0	3.40	3.85	1.64	.0647	3.57	3.81	1.63	3.35	173.9
95.0	3.16	3.49	1.59	.0565	3.24	3.54	1.53	3.20	147.2
90.0	2.91	3.16	1.53	.0482	2.92	3.37	1.42	3.07	121.3
85.0	2.66	2.85	1.47	.0423	2.63	3.25	1.35	2.98	100.9
80.0	2.43	2.58	1.43	.0376	2.39	3.12	1.29	2.89	83.8
75.0	2.22	2.36	1.37	.0342	2.18	3.05	1.24	2.84	70.4
70.0	2.01	2.13	1.32	.0308	1.97	2.98	1.19	2.78	56.9
65.0	1.82	1.94	1.28	.0276	1.80	2.89	1.15	2.75	45.9

TABLE 3

SIMULATED STEADY-STATE RUNNING LINE

(Corrected to ISA and Sea Level Static Conditions)

$\frac{N_c}{N_{Des}}$ % of Des	MA_c lb/s	$\frac{P3}{P0}$	$\frac{T3}{T0}$	WF_c lb/s	$\frac{P4}{P0}$	$\frac{T4}{T0}$	$\frac{P5}{P0}$	$\frac{T5}{T0}$	FN_c lbf
100.0	3.38	3.82	1.63	.0645	3.52	3.86	1.60	3.32	171.6
95.0	3.16	3.48	1.57	.0557	3.19	3.65	1.51	3.17	145.6
90.0	2.91	3.15	1.51	.0490	2.90	3.52	1.43	3.07	123.4
85.0	2.67	2.85	1.46	.0430	2.62	3.40	1.36	2.99	103.2
80.0	2.41	2.55	1.40	.0373	2.35	3.28	1.29	2.92	84.3
75.0	2.21	2.34	1.36	.0336	2.16	3.21	1.25	2.90	71.5
70.0	2.01	2.14	1.32	.0296	1.98	3.12	1.20	2.84	59.1
65.0	1.84	1.98	1.28	.0262	1.85	3.04	1.17	2.79	49.1

4.2 Transients

4.2.1 Experimental Data

Firstly, the experimental results are discussed, as these provide the reference parameter time traces against which the model simulations are validated, as well as, the major transient input parameter – the fuel flow time trace. Only the first set of transients – chops and bursts – were used in the validation.

A comparison of each type of transient record with its repeat run showed that the parameter test to test variation was well within the parameter signal noise values given in Table 1. Consequently, the contribution of the test to test variation between like transients was ignored in determining whether the equilibrium steady-state values had been reached by the end of a given transient.

The parameter values at the end of the transient record – after 16 seconds – were compared with the corresponding steady-state test measurements taken some 3 minutes later. The comparison showed that after 16 seconds:

a.   the spool speed, pressures and thrust were at their equilibrium values;

b.   the temperatures were some 1% from their equilibrium values; and

c.   the fuel flow value was still different from its equilibrium value.

It is possible that these differences are due to a slight heat soak effect in the engine.

The difference between the transient end point and the steady-state equilibrium fuel flow value has been calculated for both accelerations and decelerations at each of the four ranges of throttle movement, as described in section 2.2. These values are given in Table 4 and are expressed as a % of the 100% N_c/N_{Des} value of WF_c. As these differences are of the same order as the fuel flow signal noise, which is $\pm 3.55\%$, their significance could be questioned. However, given the consistency with which the magnitude of these differences were measured for repeat transients and the consistency of the sign for accelerations or decelerations, the difference is believed to be a real engine effect and not due to measurement noise.

The results of Table 4 show that at the end of the transient record the acceleration fuel flow is still greater than and the deceleration fuel flow is still less than the corresponding equilibrium steady-state value. Clearly, after 16 seconds the fuel flow and hence the engine has not reached a true steady-state condition. It is most likely that the engine is still adjusting to bulk temperature effects.

TABLE 4

DIFFERENCE BETWEEN STEADY-STATE AND TRANSIENT END POINT FUEL-FLOW VALUES

$\%WF_{DES}$ (% of WF value at 100% N_C/N_{Des})

ACCEL $\%N_C/N_{Des}$	$\dfrac{WF - WF_t}{\%WF_{Des}}$	DECEL $\%N_C/N_{Des}$	$\dfrac{WF - WF_t}{\%WF_{Des}}$
82–101	–5.56	101–82	4.63
91–101	–4.63	101–91	4.02
68–91	–3.55	91–68	2.78
86–96	–2.32	96–86	2.47

4.2.2 Model Validation

In validating the open-loop transient model only four parameters,

a. the input fuel flow time trace,
b. the inlet temperature of the day,
c. the spool moment of inertia, and
d. the component lumped volumes

had to be determined. The first two are specified by the particular experimental transient being matched. However, as detailed previously in section 3.2.6, the model fuel flow input can only be a smoothed – no noise – estimate of the measured fuel flow trace. The last two are calculated from the geometry of the engine and are the same for all transients. The design point Station Vector and Brick Data values have been set by the Calibration of Section 4.1 and these values were not changed in the validation runs.

The initial set of simulations used the smoothed fuel flow signal, refer 3.2.6, as the input fuel flow time trace. These simulations showed a reasonable match to the initial steady-state portion of the transient record. But from the start of the

transient to the end of the record, at 16 seconds, the acceleration simulations consistently overpredicted the parameter values. Conversely, the decelerations simulations consistently underpredicted the parameter values. Overall, the simulated transients were of similar shape to the experimental trace but with either a positive or negative translation – bias – depending on whether the simulation was an acceleration or deceleration.

It was apparent from these initial results that an improved match could be obtained by appropriately shifting the input fuel flow time trace. The initial steady-state portion of the trace was left unchanged and the transient portion was depressed or increased by an amount equal to the measured difference between the equilibrium steady-state and the transient end point fuel flow values, as given in Table 4. The transition from zero change to the full amount was made over the first half second of the transient portion. The introduction of this shift resulted in a good match between the simulated and measured transients. The typical match for an acceleration is shown in Figures 4A, 4B and 4C and that for a deceleration is shown in Figures 5A, 5B and 5C.

Given the above adjustment to the input fuel flow trace the remaining differences between the simulated and measured parameter transients can be attributed to the limitations of the steady-state match. These differences are consistent with the models under or over prediction of the steady-state running line at a particular N_c/N_{Des}, as shown in Figures 3A, 3B and 3C. Furthermore, these errors in the match at the start and end points of the transient cause most of the mismatch in the transient portion of the curve. Simply, this is because the start and end points are different. Otherwise, the shape of the simulated transients parallels the experimental trace.

4.2.3 Sensitivity of Simulation

Having obtained good predictions with the open-loop model, a series of parametric studies was carried out to determine the sensitivity of the simulation to changes – errors – in the four input parameters.

The 2 σ noise band on the fuel flow signal was estimated at $\pm$ 3.55% of WF_c value at 100% N_c/N_{Des}, as given in Table 1. The sensitivity of the simulation to errors in the fuel flow signal is shown in Figures 6A, 6B and 6C. The two simulations used the input fuel flow signal of Figure 4 plus 3.55% for the first and minus 3.55%

for the second. The results of Figure 6, shows that all the output parameter values move in the same direction as the fuel flow change. A comparison of these results with those of Figure 4 shows that the mismatch between the simulated and experimental transients falls within the range of parameter values simulated by a $\pm2\,\sigma$ error band on the fuel flow. This result is typical of all the other transients. Furthermore, the simulations sensitivity to fuel flow input errors, at other operating points, can be readily calculated from the steady-state gains given in Appendix C-2.

The accuracy of the inlet temperature measurement was assessed at $\pm3K$ i.e. $\pm1.05\%$ of ISA TO. The sensitivity of the simulation to this level of inlet temperature error is illustrated by Figures 7A and 7B. Again the same input data as Figure 4 is used but the inlet temperature is increased by 3K in the first and decreased by 3K in the second. The results of Figure 7, shows that all the outlet parameter values move in the opposite direction to the inlet temperature change. Clearly, the temperature error has a smaller but opposite effect to the fuel flow error. However, the relative smaller changes in the parameter values is more a consequence of the larger uncertainty assigned to the fuel flow signal. A comparison of Figures 7 and 4, shows that a reduction in the inlet temperature of 3K would improve the match for spool speed, all pressures and thrust.

The importance of the TO error is related to the method of calibrating the steady-state model. Here, the experimental data was corrected back to ISA conditions and the model was calibrated at ISA. Therefore, a bias with respect to inlet temperature may be present. Indeed, the use of a lower than actual TO value – although a reduction of some 6K is required – improved most of the transient simulations.

The moment of inertia of the Couguar turbojet would be within $\pm5\%$ of the calculated value. The simulation of the acceleration transient of Figure 4 with a $\pm10\%$ change in the inertia did not result in a change in the transient trace. The inertia needed to be increased some 25% before the trace was visibly moved. A more appropriate way of showing the sensitivity of the simulation is to show its effect on the time constant. The fuel-step simulation of section 4.3 was used and the results are shown in Figure 8. Clearly, the model is responding to changes in spool inertia and the simulated time constant is proportional to the magnitude of the inertia. However, there is little to be gained from pursuing a more accurate estimate of the spool inertia as the shape of the transient trace is being correctly predicted with $I_{cgr} = 0.00612$ lbf ft s^2 and changes within $\pm5\%$ I_{cgr} will not affect it.

The component volumes would be within $\pm$ 5% of the calculated values. Simulations showed that the small volumes appropriate to the Couguar turbojet had no effect on the transient response. In fact, to show an effect the volumes had to be in...ased some three orders of magnitude. However, this insensitivity is realistic as the transients measured in the test program had no high frequency oscillations on the parameter-time traces. Such oscillations occur in much larger engines. In the transient model, it is the function of the component volumes to account for the high frequency oscillations. But here the scale of the engine is too small for this effect to be important.

4.2.4   Future Improvements

In summary, the calibrated TURBOTRANS model has provided good simulations of the experimental transients. However, the accuracy of the model has been limited by the noise on the primary input signal - the fuel flow. Clearly, the fuel flow signal should be improved before further transient work or the development of a more accurate model is pursued. Furthermore, the simulations have shown that the model development should be concentrated on improving the steady-state match, refer section 4.1. Also the possibility of including bulk temperature effects into the the model should be considered. Finally, given that the shape of the transient trace is good and the simulations have shown effectively no sensitivity to realistic changes in the spool moment of inertia and component volumes, there is no need to obtain more accurate measures of these parameters.

4.3   Parameter Time Constants and Steady-State Gains

The dynamics of a single-spool gas turbine can be approximated by a first-order transfer function model (8). Naturally, the accuracy of such a simplified model is not as good as the full thermodynamic model, but it is sufficient to produce a satisfactory control system (9). In contrast, the full thermodynamic model cannot be used as a real-time model. The task here was to provide estimates of the dynamic parameters, i.e. the steady state gain and time constant, which would be used in the future development of a real-time transfer function model of the Couguar turbojet.

In a simple single-spool turbojet, like the Couguar, there is only one control input variable - the fuel flow. However, the transient response of a number of engine parameters - the output - may need to be modelled. The actual number will

depend on the desired complexity of the engine controller. In the simplest control case, only the spool speed would need to be modelled. In this study, the steady-state gain and time constant was determined for each of the nine main engine parameters.

To define the first-order transfer function model, which relates the outputs to the inputs, two dynamic parameters need to be determined. These are the time constant and the steady-state gain. The time constant is a measure of the response time of a parameter output to a given fuel step input. For a first-order system, it is equal to the time taken for the parameter to reach a value which is 63% of the difference between the final and initial steady-state values. For a fuel step input, the steady-state gain is the change in a steady-state parameter value divided by the corresponding change in the fuel flow. Essentially, the gain is the gradient of the steady-state running line with respect to fuel flow.

As the overall engine response is non-linear, the value of the time constant and steady-state gain appearing in the first order transfer function must be varied across the operating range of the turbojet; their values being dependent on the location of the current engine operating point. For this reason, the two dynamic parameters were determined at 5% N_{Des} intervals across the operating range of the Couguar turbojet – from 65% N_{Des} to 100% N_{Des}. The transfer function model is therefore treated as a piecewise linear model and the seven values of each dynamic parameter, provided here, can be used in a look-up table.

The parameter steady-state gains were calculated using the experimental running line data of Table 2. These results are given in Table 5. For comparison purposes, the gains were also calculated using the TURBOTRANS model but these results are presented in Appendix C-2 as the experimental gains are assessed to be the more accurate estimates and the values to use. The results of Section 4.1 showed that, although slight, there is a mismatch between the experimental and simulated running lines. Consequently, the gains calculated using the simulated running line data would be and were different from those calculated using the experimental data; the difference being in proportion to the steady-state mismatch.

The parameter time constants were generated using the open-loop, transient form of the TURBOTRANS model. Experimental confirmation of the results will be possible, in the near future, as a digital open-loop controller, capable of inputting small fuel steps, is under development. The simulations were done at each 5% N_{Des} interval from 65% N_{Des} to 100% N_{Des}; this was done for both positive and negative

fuel step inputs. The magnitude of these fuel steps corresponded to the 5% N_{Des} increments.

The program predicted, at a given operating point, essentially the same time constant whether the fuel step was an acceleration or a deceleration. Therefore, these two results were averaged to provide a single estimate. The resultant parameter time constants for the entire operating range are given in Table 6. There was some deviation between the acceleration and deceleration time constants within the range 65% N_{Des} to 75% N_{Des}. These variations were of the order of 5 to 20%, with the accelerations generally resulting in higher parameter time constants – the exceptions being T4, T5. It is most likely that these deviations are due to the problems in the ODP solution procedure when fuel flow is used to specify the ODP – especially at spool speeds around 65% N_{Des}. This has been discussed previously in Section 3.2.5.

The transients measured in the experimental program – typically accelerations or decelerations over a range greater than 20% N_{Des} – had no overshoots in the Couguar engine parameter traces but rather were single valued curves. With the exception of T4 and T5, the program simulated a similar parameter response given a 5% N_{Des} fuel step input. The response of T4 and T5 progressively exhibited overshoot as the operating speed was reduced from 90% N_{Des} to 65% N_{Des}. This overshoot is also reflected by the time constants for T4 and T5 decreasing as the operating speed declines – refer Table 6. In contrast, the time constants for all the other engine parameters increased as the operating speed was reduced.

For a simple spool speed controller, a first-order transfer function should be appropriate to model the dynamics of the Couguar engine. However, for temperature controllers and engine diagnostic work, a higher order transfer function may be required to model the response of T4 and T5.

TABLE 5

PARAMETER STEADY-STATE GAINS FROM EXPERIMENTAL DATA

(Δ Parameter/ Δ WF$_c$)

N Range for Fuel Step % of Des	Engine Parameter								
	$\frac{N_c}{N_{des}}$	MA$_c$	$\frac{P3}{P0}$	$\frac{T3}{T0}$	$\frac{P4}{P0}$	$\frac{T4}{T0}$	$\frac{P5}{P0}$	$\frac{T5}{T0}$	FN$_c$
95 – 100	610	29.3	43.9	6.1	40.2	32.9	12.2	18.3	3256.
90 – 95	603	30.1	39.8	7.2	38.5	20.5	13.3	15.7	3120.
85 – 90	847	42.4	52.5	10.2	49.2	20.3	11.9	15.3	3458.
80 – 85	1064	48.9	57.4	8.5	51.1	27.7	12.8	19.2	3638.
75 – 80	1470	61.8	64.7	17.6	61.8	20.6	14.7	14.7	3941.
70 – 75	1470	61.8	67.6	14.7	61.8	20.6	14.7	17.6	3970.
65 – 70	1563	59.4	59.4	12.5	53.1	28.1	12.5	9.4	3438.

TABLE 6

PARAMETER TIME CONSTANTS FROM SIMULATION

(Seconds)

N Range for Fuel Step % of Des.	Engine Parameter								
	$\frac{N_c}{N_{des}}$	MA$_c$	$\frac{P3}{P0}$	$\frac{T3}{T0}$	$\frac{P4}{P0}$	$\frac{T4}{T0}$	$\frac{P5}{P0}$	$\frac{T5}{T0}$	FN$_c$
95 – 100	.36	.40	.23	1.33	.20	.82	.23	.80	.18
90 – 95	.48	.52	.35	1.46	.32	.62	.34	.52	.28
85 – 90	.53	.57	.40	1.52	.37	.50	.40	.37	.34
80 – 85	.57	.60	.43	1.57	.39	.48	.43	.33	.35
75 – 80	.84	.83	.65	1.82	.60	.38	.68	.22	.52
70 – 75	.91	.90	.72	1.89	.68	.38	.69	.24	.54
65 – 70	1.12	1.08	.92	2.07	.88	.39	.76	.29	.60

5. CONCLUSION

An open-loop, transient, thermodynamic model of the single-spool Couguar turbojet has been developed using the generic engine model TURBOTRANS.

The open loop model provided good simulations of a range of measured transients, both accelerations and decelerations. The validation showed that most of the mismatch between the simulations and the measured transients was a consequence of the steady-state mismatch. That is, the difference was generally due to a bias shift of the parameter time trace rather than a different trace shape.

As to improving the current model, the investigation has shown that the following areas require attention:

a. The accuracy of the temperature measurements T4, T5 and the fuel flow signal WF need to be improved before a more accurate calibration of the model against the measured steady-state running line is pursued.

b. The introduction of more representative component maps are required. There is little further improvement to be gained from scaling the design point values of generic maps. For example, in a compressor map this means a translation of the total map whereas the present steady-state mismatch requires unequal shifts in the various speed lines of the compressor map.

c. The possibility of introducing bulk temperature effects into the model should be studied. In the present model, this was accounted for by adjusting the input fuel flow signal prior to running the model simulation.

The open-loop model also provided estimates of the time constants of the Couguar turbojet as required for the development of a real-time transfer function model of the Couguar turbojet.

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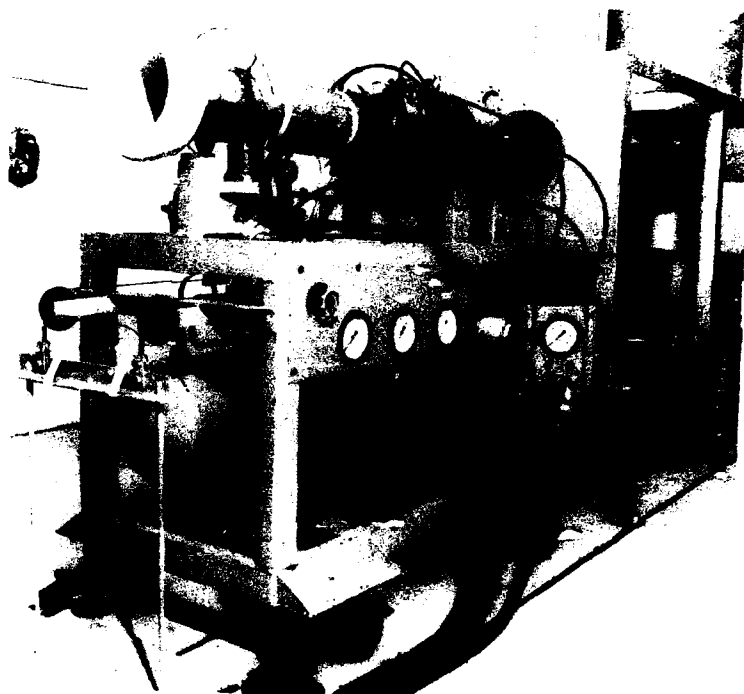
FIG 1.   COUGUAR TURBOJET MOUNTED IN TEST STAND
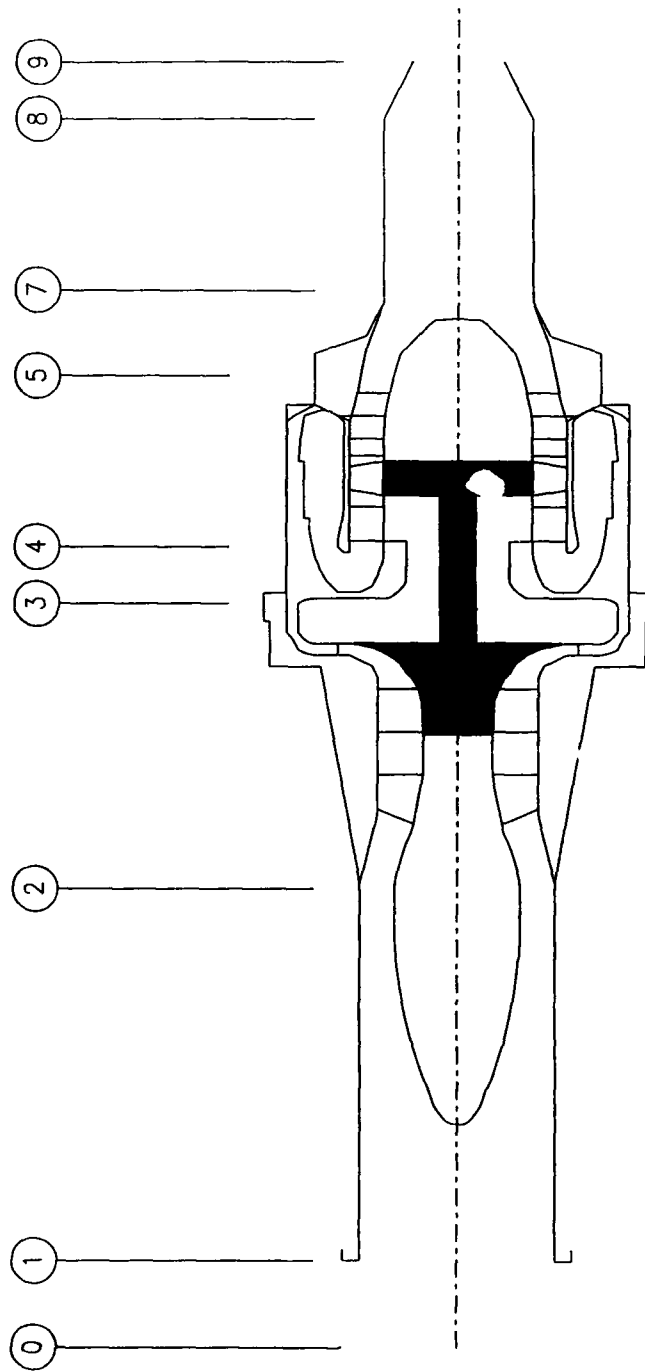
FIGURE 2 — SCHEMATIC OF COUGUAR TURBOJET

COUGUAR TURBOJET

Experiment. ——
Simulation. — — —
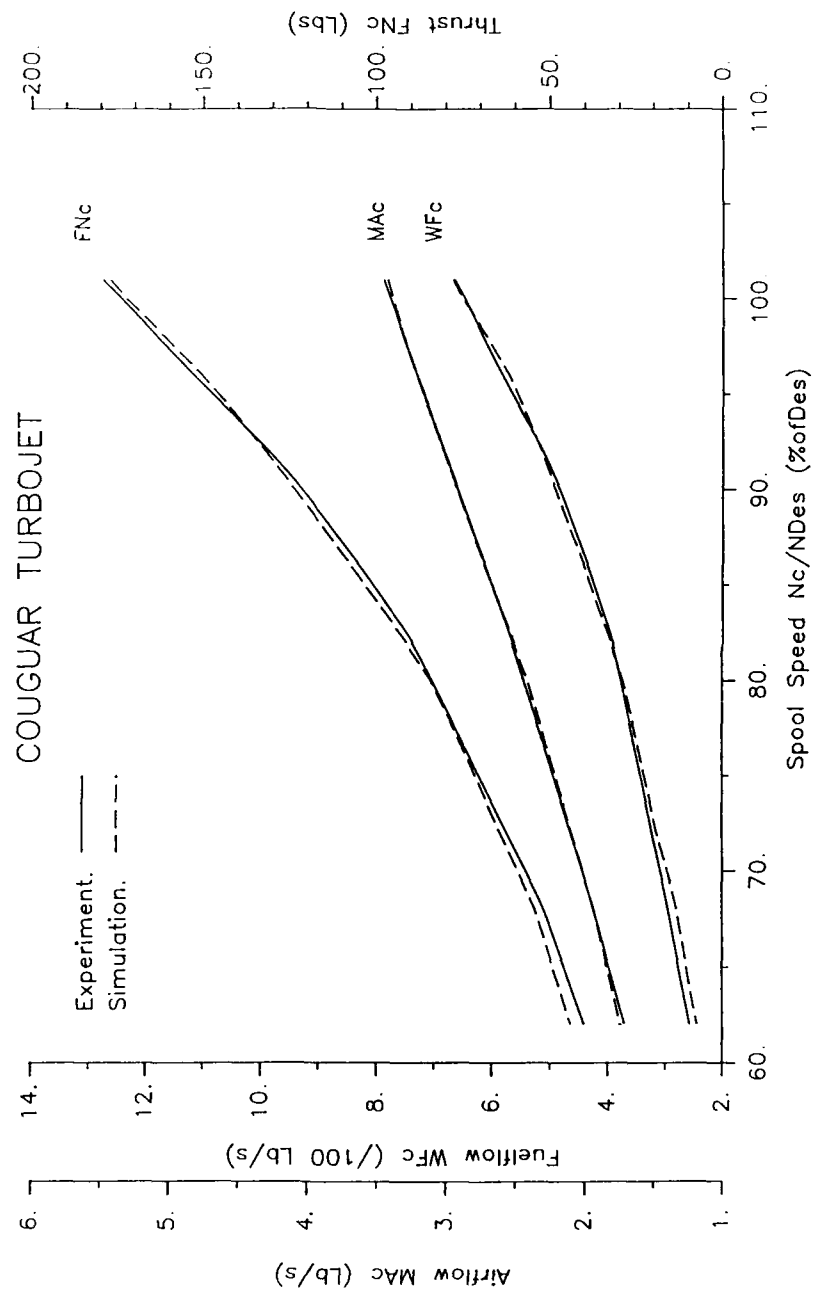
FIGURE 3A — STEADY-STATE RUNNING LINE SIMULATION

COUGUAR TURBOJET

Experiment. ———
Simulation. – – –

P3/P0
P4/P0

P5/P0

Pressure Ratio

Spool Speed Nc/NDes (%ofDes)
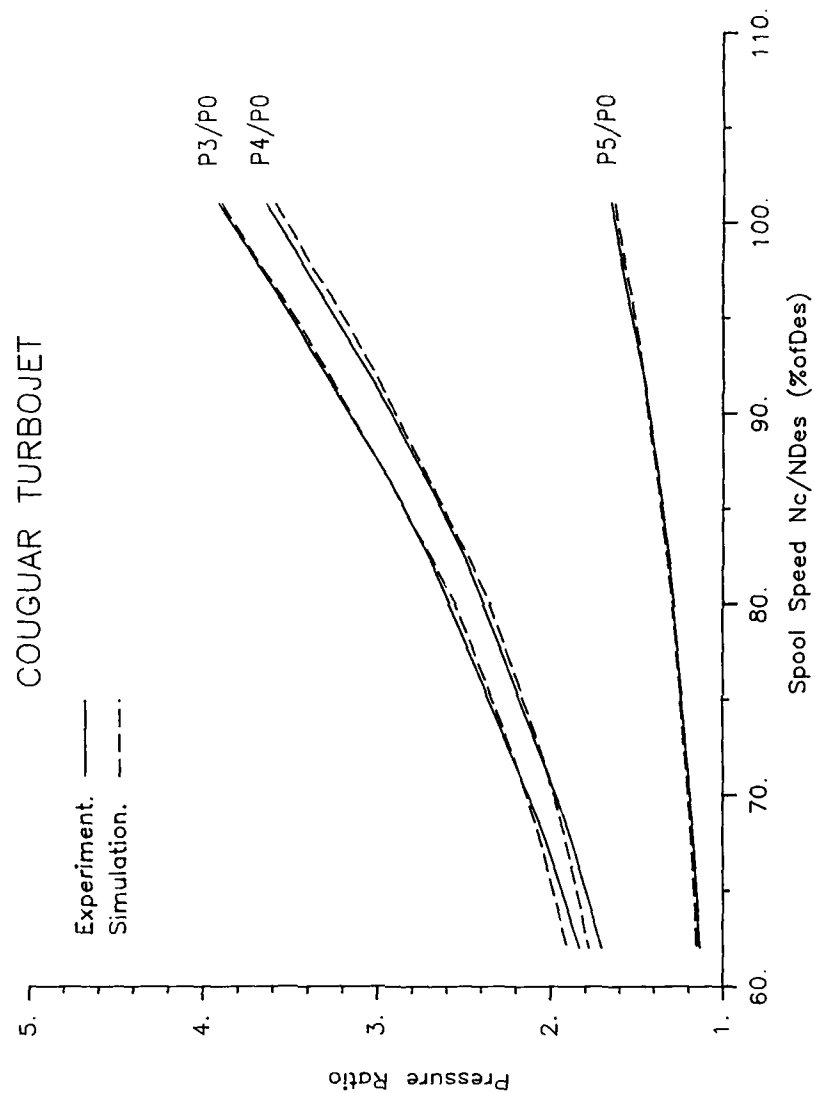
FIGURE 3B   — STEADY-STATE RUNNING LINE SIMULATION — PRESSURE RATIOS

COUGUAR TURBOJET

Experiment. ————
Simulation. — — —

T4/T0

T5/T0

T3/T0

Spool Speed Nc/NDes (%ofDes)

Temperature Ratio

5. 4. 3. 2. 1.

60. 70. 80. 90. 100. 110.
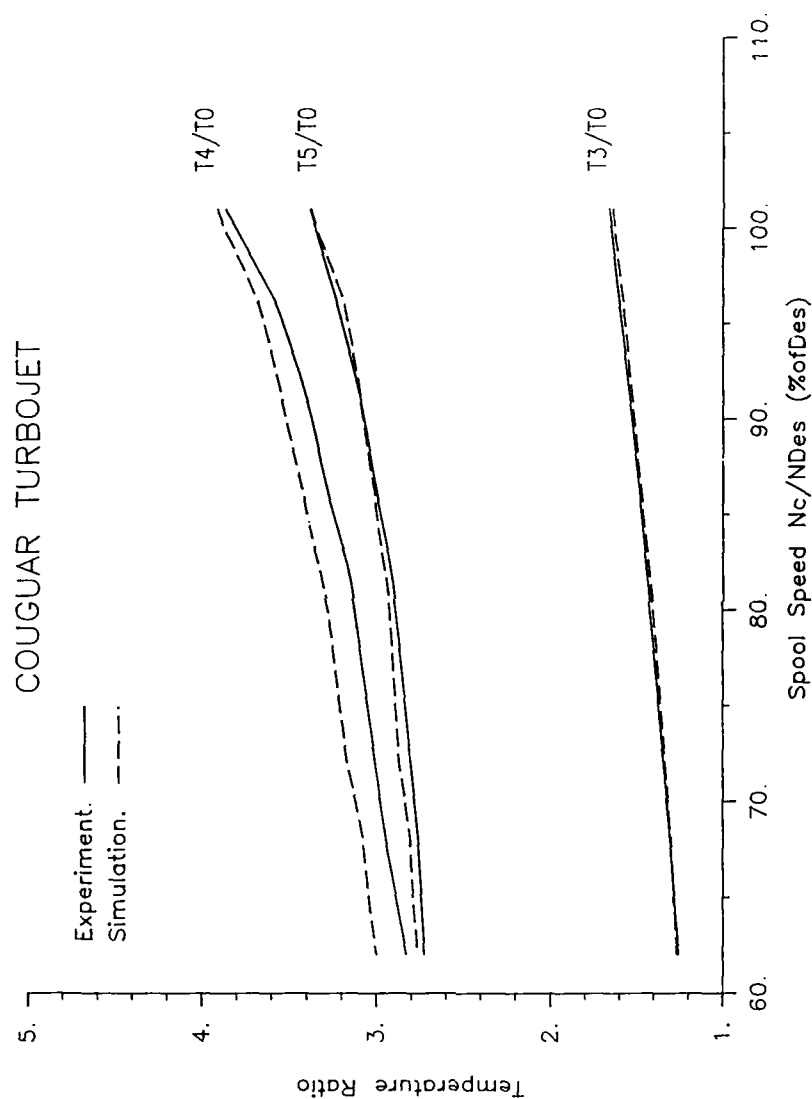
FIGURE 3C -- STEADY-STATE RUNNING LINE SIMULATION - TEMPERATURE RATIOS

COUGUAR TURBOJET

Experiment. ———
Simulation. – – –

FN

Nc/NDes

MA
WF

Thrust FN (Lbs)

Spool Speed Nc/NDes (%ofDes)

Time (Seconds)

Fuelflow WF (/100 Lb/s)

Airflow MA (Lb/s)
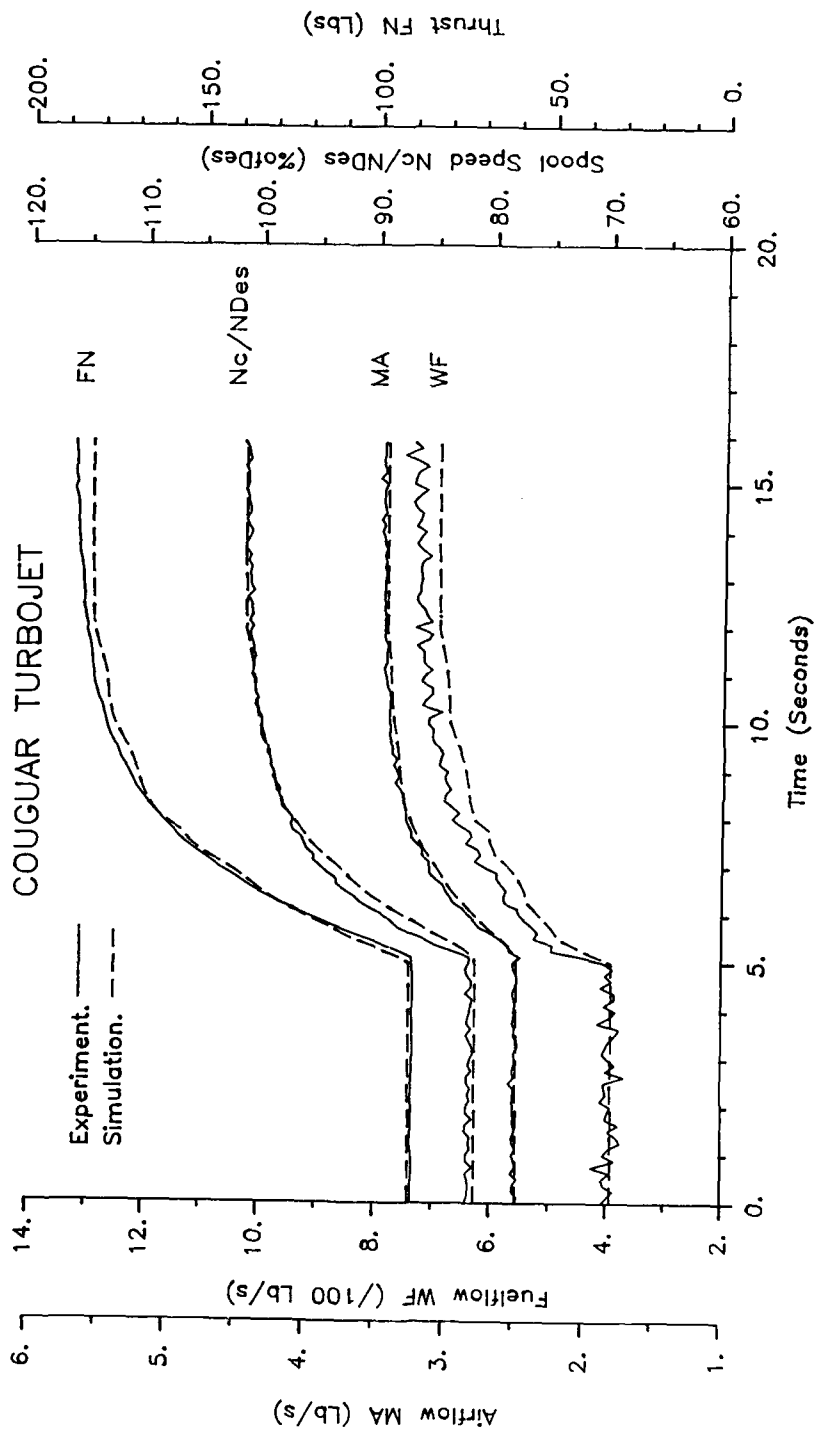
FIGURE 4A — TYPICAL ACCEL. SIMULATION

COUGUAR TURBOJET

Experiment. ———
Simulation. – – –

P3/P0
P4/P0

P5/P0

Time (Seconds)
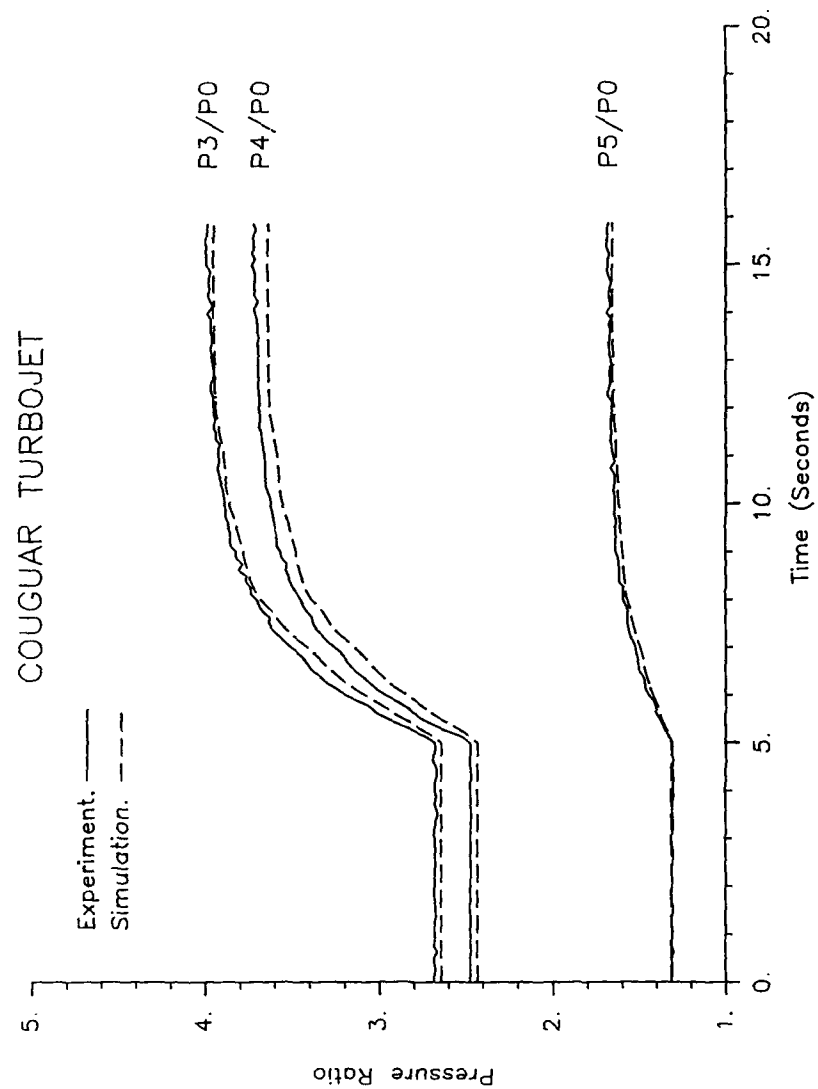
Pressure Ratio

FIGURE 4B   – TYPICAL ACCEL. SIMULATION – PRESSURE RATIOS

COUGUAR TURBOJET

Temperature Ratio

T4/T0
T5/T0
T3/T0

Experiment. ———
Simulation. – – –

Time (Seconds)
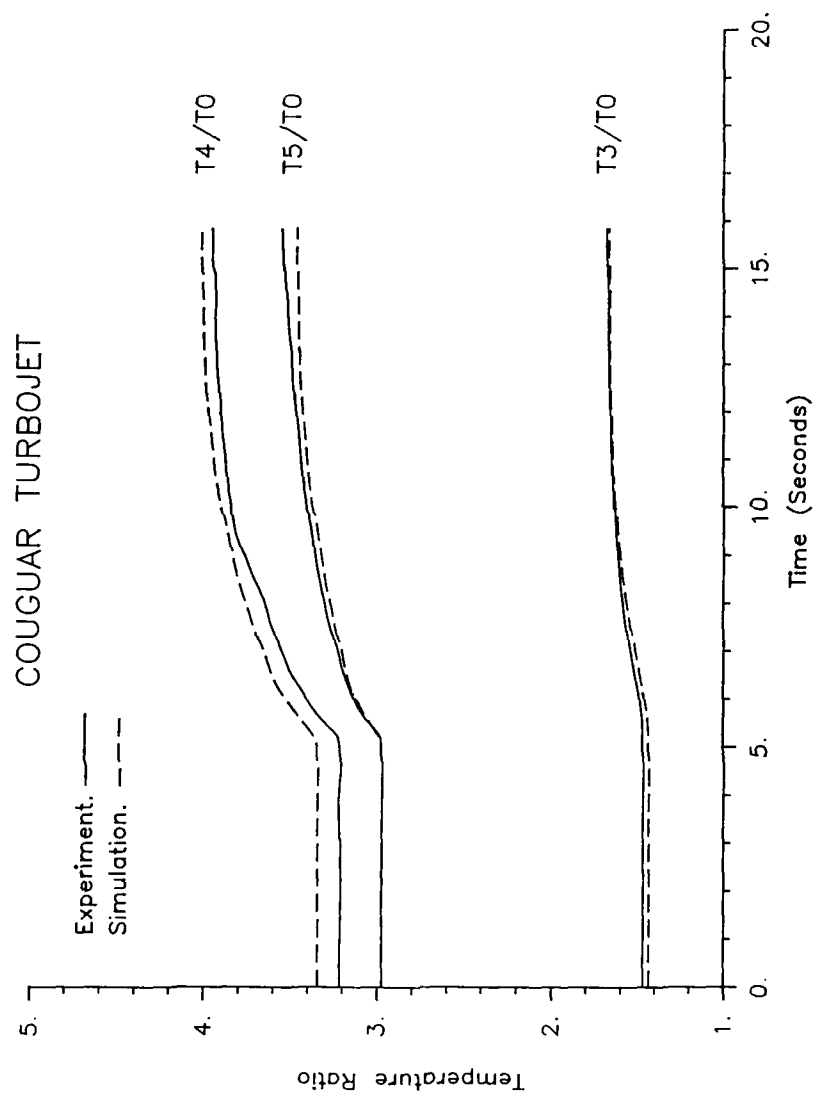
FIGURE 4C – TYPICAL ACCEL. SIMULATION – TEMPERATURE RATIOS

COUGUAR TURBOJET

Experiment. ———
Simulation. — —

FN

Nc/NDes

MA

WF

Thrust FN (Lbs)

Spool Speed Nc/NDes (%ofDes)

Time (Seconds)

Fuelflow WF (/100 Lb/s)

Airflow MA (Lb/s)
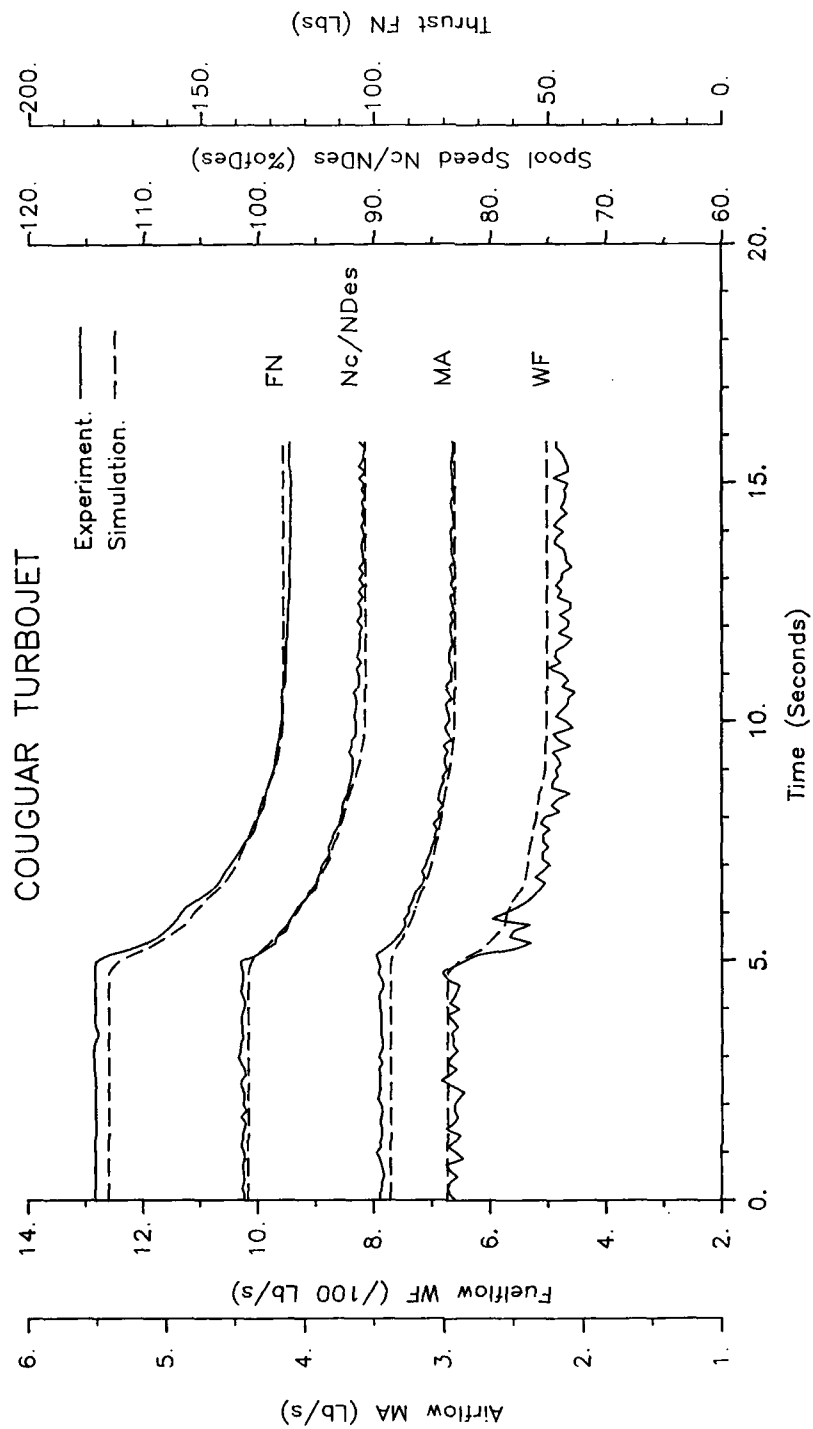
FIGURE 5A — TYPICAL DECEL. SIMULATION

COUGUAR TURBOJET

Experiment. ————
Simulation. — — —

P3/P0
P4/P0

P5/P0

Pressure Ratio

Time (Seconds)
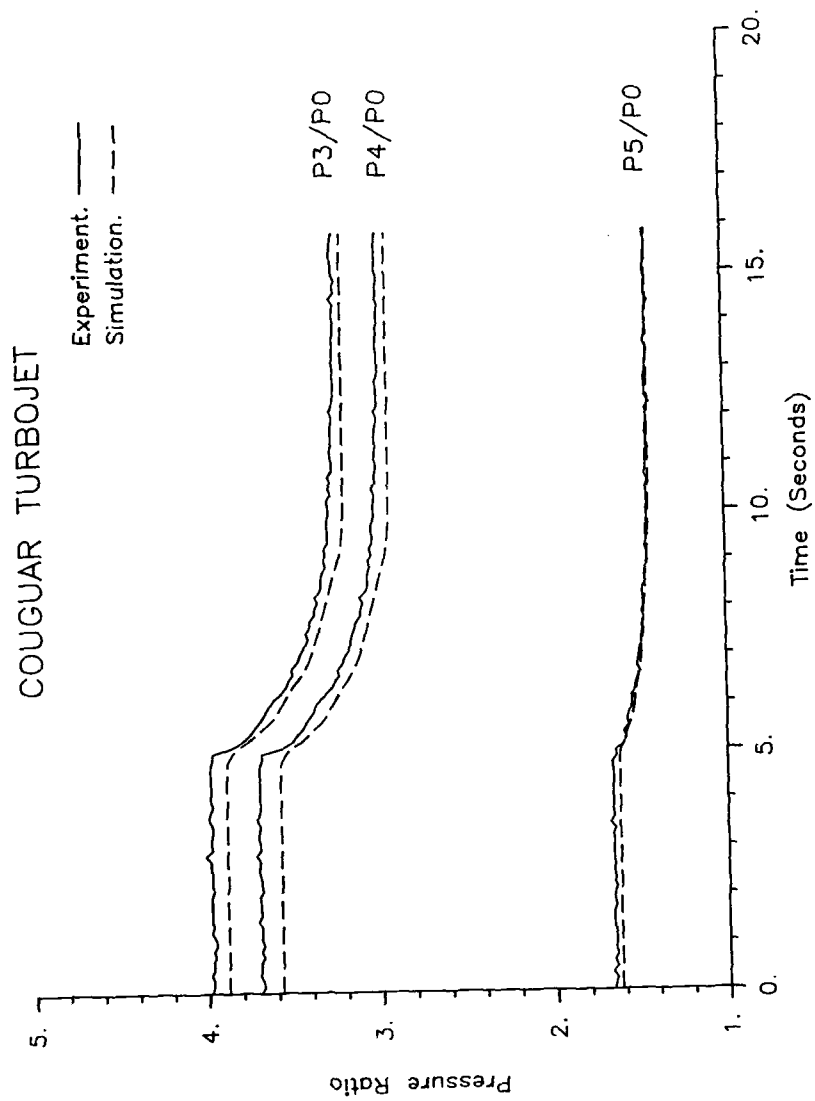
FIGURE 5B — TYPICAL DECEL. SIMULATION — PRESSURE RATIOS

COUGUAR TURBOJET

Experiment. ————
Simulation. — — —

T4/T0
T5/T0
T3/T0

Temperature Ratio

Time (Seconds)
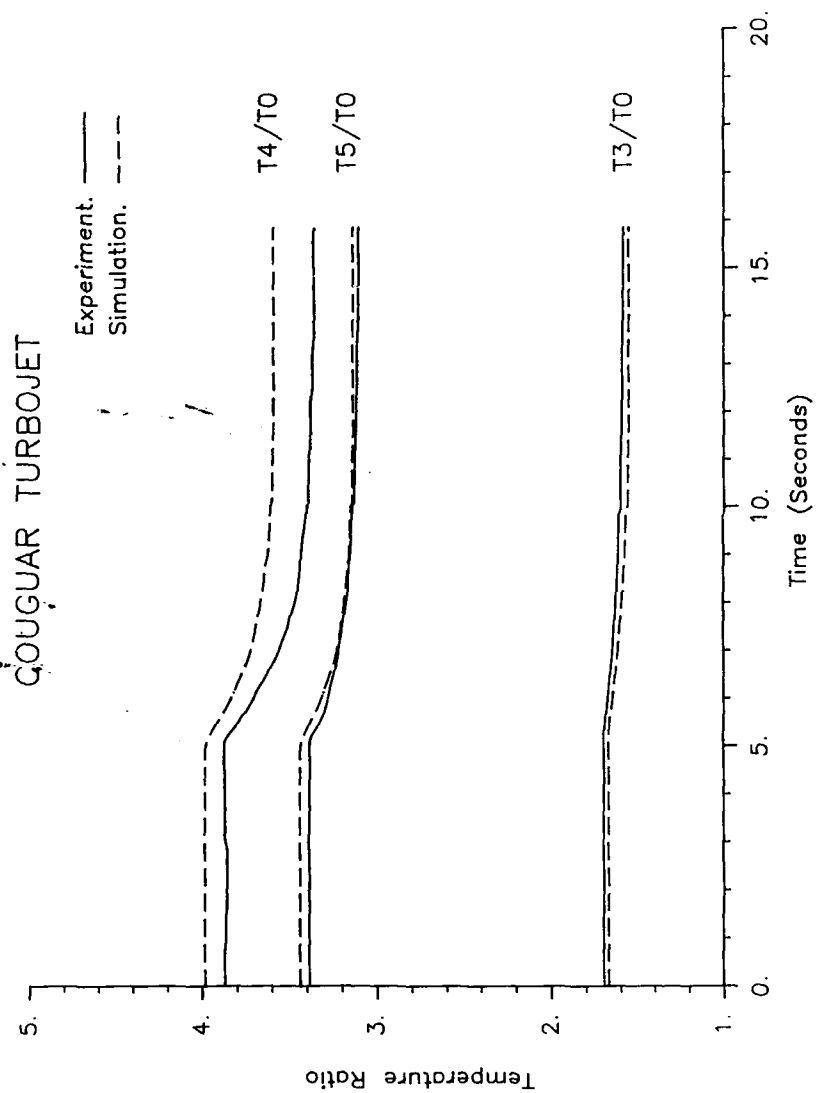
FIGURE 5C — TYPICAL DECEL. SIMULATION — TEMPERATURE RATIOS

COUGUAR TURBOJET

Fuelflow input signal has
a 2 sigma noise band of
+/- 3.55 %ofDes WF

FN   +
       −

Nc/NDes +
         −

MA   +
       −

WF   +
       −

Time (Seconds)

Thrust FN (Lbs)

Spool Speed Nc/NDes (%ofDes)

Fuelflow WF (/100 Lb/s)

Airflow MA (Lb/s)
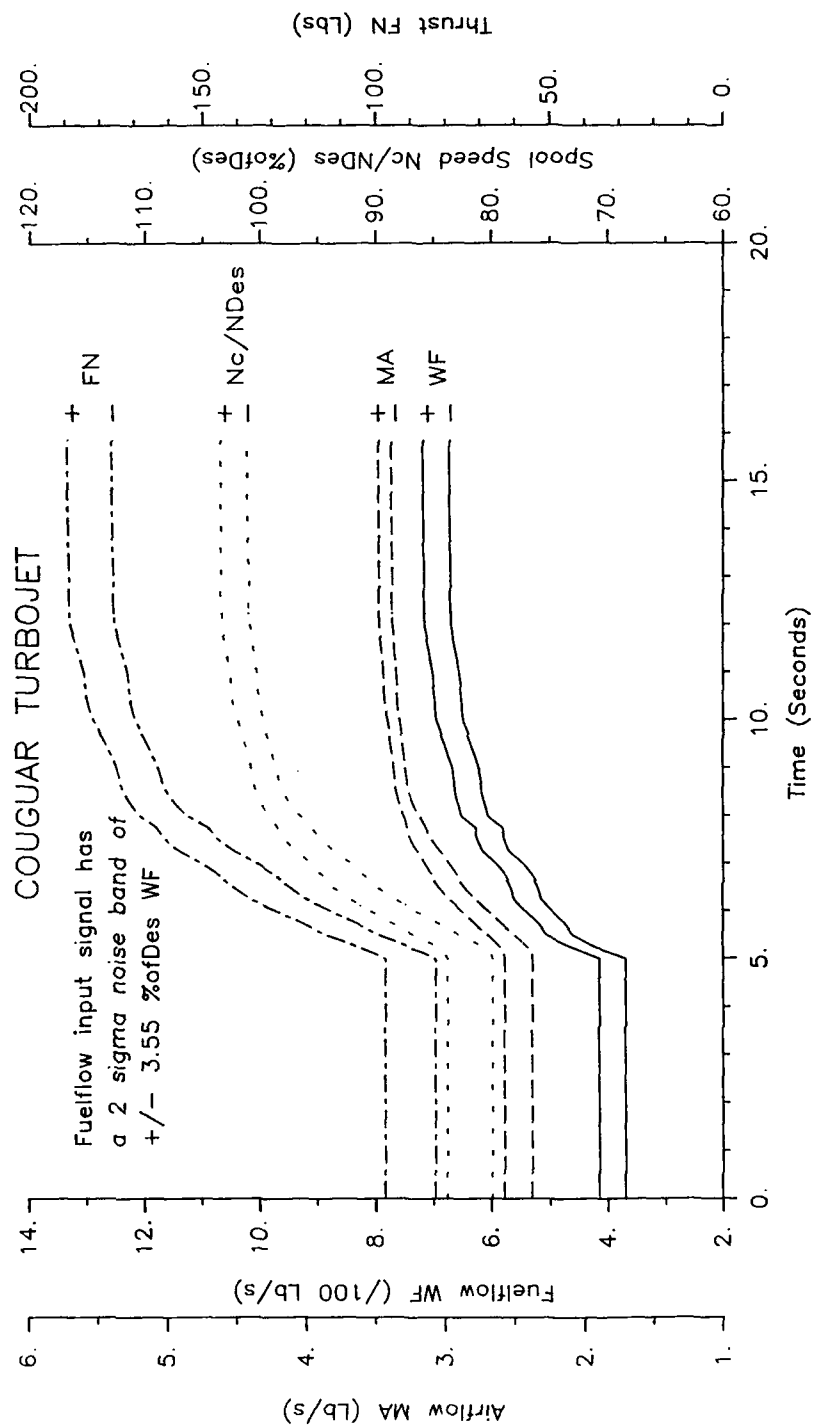
FIGURE 6A — SENSITIVITY OF SIMULATION TO FUEL INPUT ERRORS

COUGUAR TURBOJET

Fuelflow input signal has
a 2 sigma noise band of
+/- 3.55 %ofDes WF

+ P3/P0
-
+ P4/P0
-

± P5/P0

Pressure Ratio

Time (Seconds)
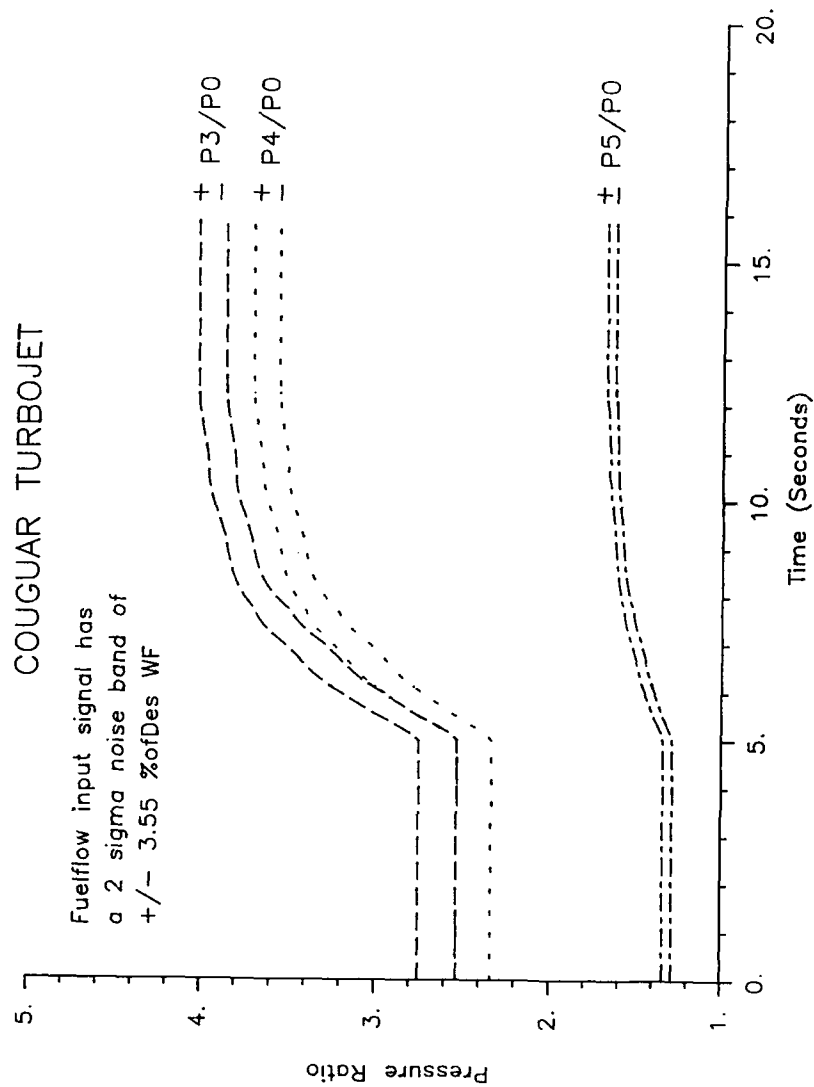
FIGURE 6B — SENSITIVITY OF SIMULATION TO FUEL INPUT ERRORS — PRESSURE RATIOS

COUGUAR TURBOJET

Fuelflow input signal has
a 2 sigma noise band of
+/- 3.55 %ofDes WF

+ T4/T0
-

+ T5/T0
-

+ T3/T0
-

Temperature Ratio

Time (Seconds)
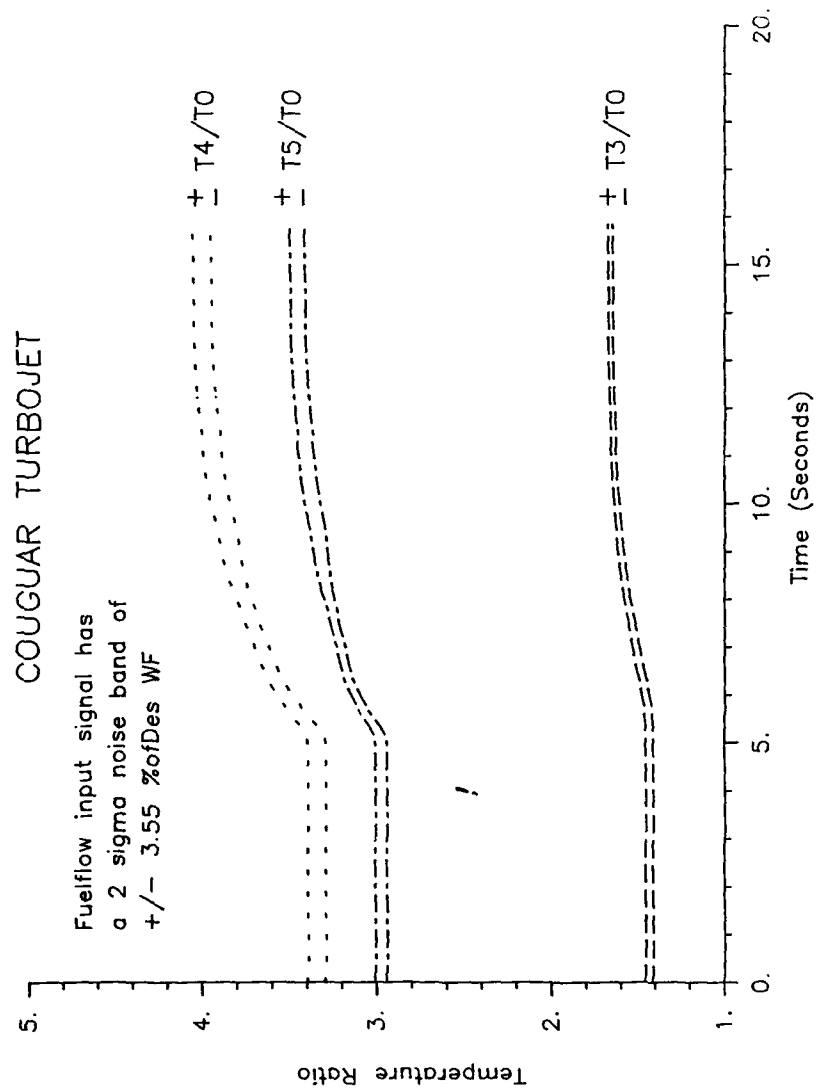
FIGURE 6C — SENSITIVITY OF SIMULATION TO FUEL INPUT ERRORS — TEMPERATURE RATIOS

COUGUAR TURBOJET

Inlet Temperature
uncertainity is
+/− 1.05 %ofISA TO

FN

Nc/NDes

MA

WF

Thrust FN (Lbs)

Spool Speed Nc/NDes (%ofDes)

Time (Seconds)

Fuelflow WF (/100 Lb/s)

Airflow MA (Lb/s)
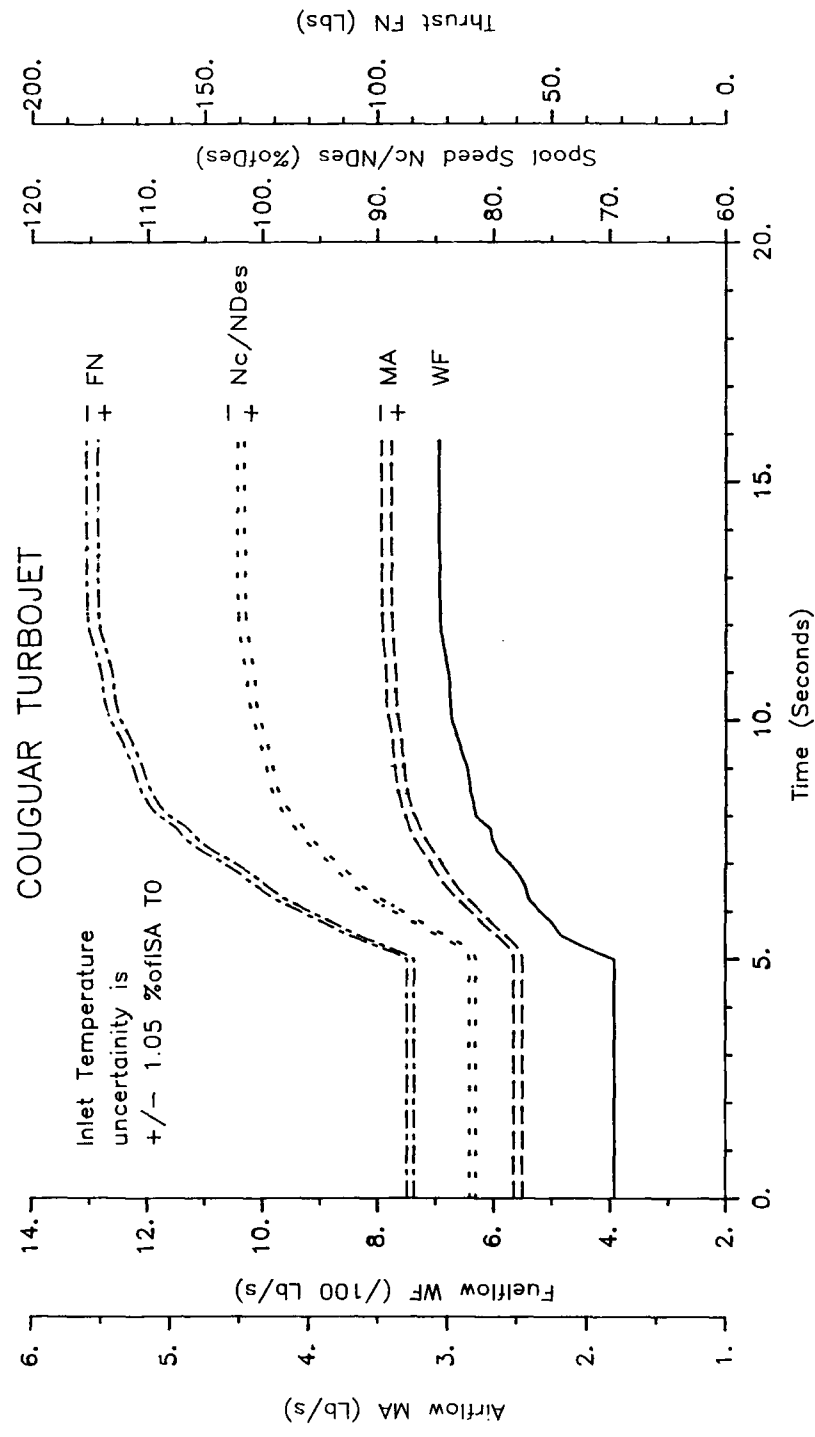
FIGURE 7A −SENSITIVITY OF SIMULATION TO INLET TEMPERATURE ERRORS

COUGUAR TURBOJET

Inlet Temperature
uncertainity is
+/- 1.05 %ofISA TO

$\mp$ + P3/P0
$\mp$ + P4/P0
$\mp$ + P5/P0

Pressure Ratio

Time (Seconds)
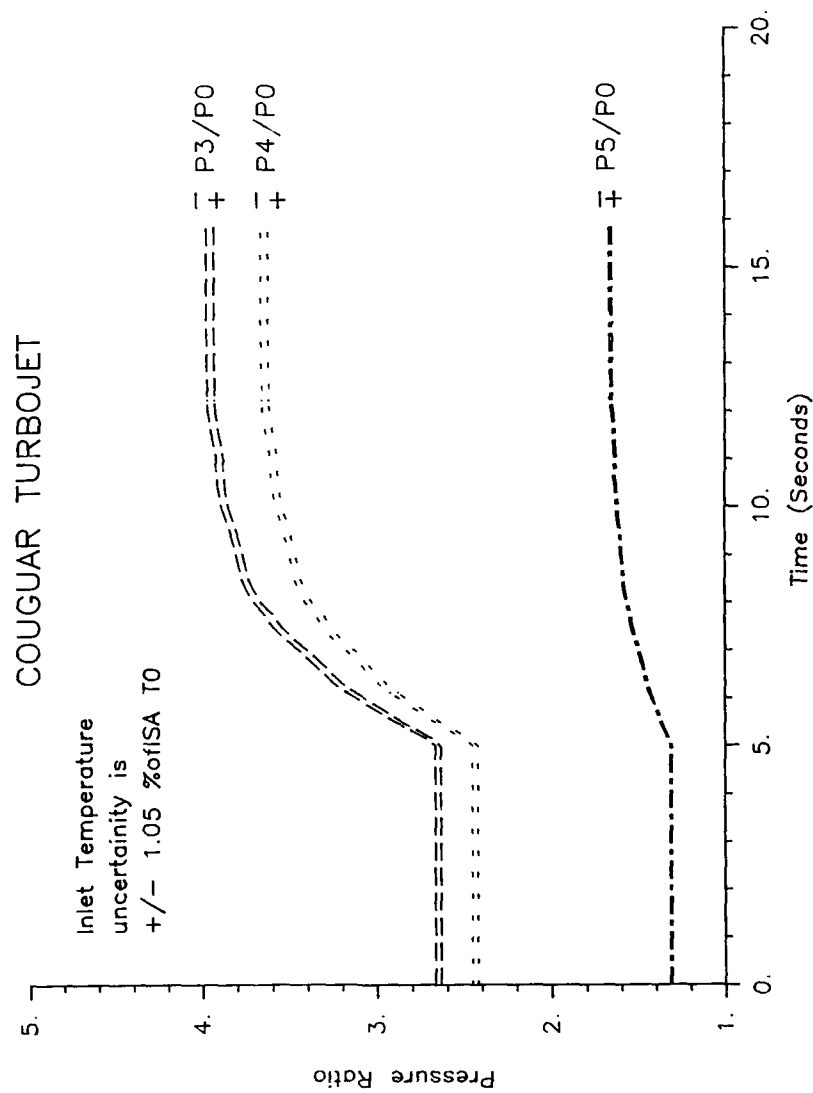
FIGURE 7B —SENSITIVITY OF SIMULATION TO INLET TEMPERATURE ERRORS — PRESSURE RATIOS

COUGUAR TURBOJET

Nc/NDes

P3/P0

Time Constant (s)

1.5

1.0

.5

.0

.0   1.0   2.0   3.0   4.0

Relative Moment of Inertia (I/Icgr)
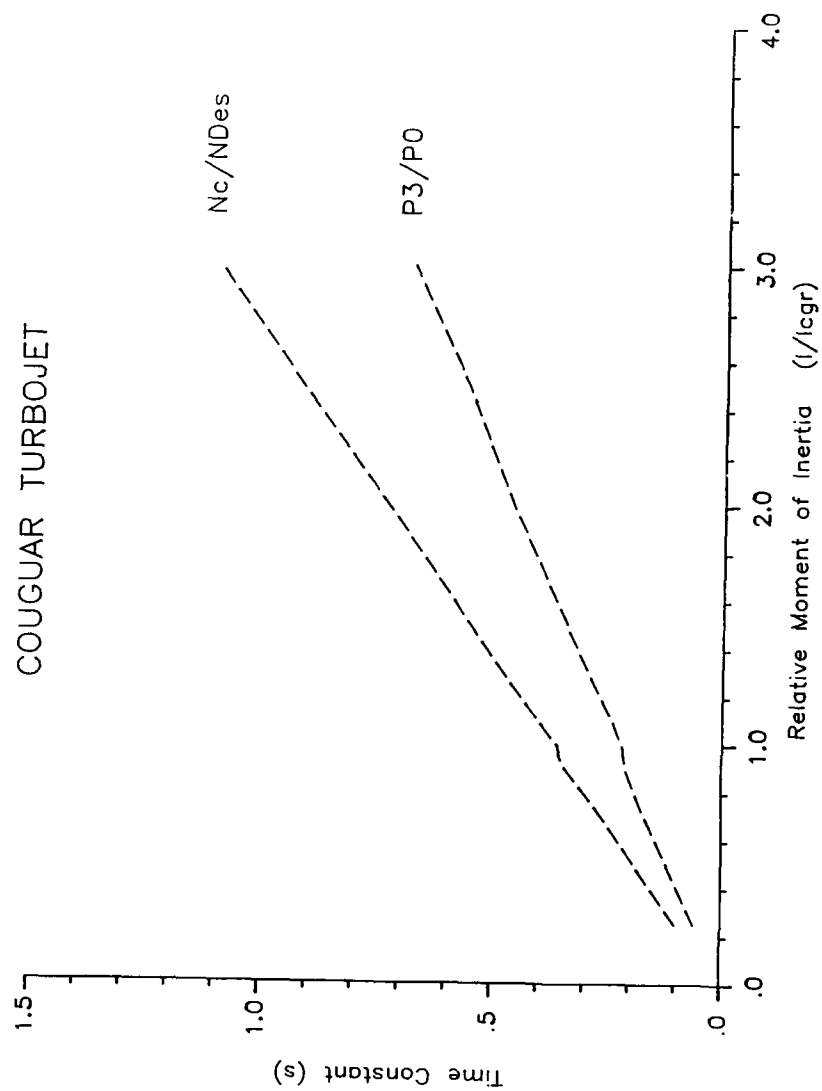
FIGURE 8 — SENSITIVITY OF SIMULATION TO SPOOL INERTIA

APPENDIX A: Measured Parameters

Channel	Parameter
0	$P0$
1	$P2_s$
2	$T2$
3	$P2$
4	–
5	$T3$
6	$P3$
7	$P3_s$
8	$T4$
9	$P4$
10	$P4_s$
11	$T5$
12	$P5$
13	$P5_s$
14	PLA
15	FN
16	ΔP_{is}
17	TWF_{in}
18	TWF_{out}
19	$T0$
20	WF_{in}
21	WF_{out}
22	N
23	–
24	–
25	–
26	WF_{in}
27	WF_{out}

APPENDIX B-1: Turbotrans Input Datafile Cipher

```
********************************************************************************
*************              TURBOTRANS DATA INPUT FILE             *************
*************              SAMPLE FORMAT WITH DEFINITIONS          *************
*************              COUGUAR SINGLE-SPOOL ENGINE             *************
*************              OPEN-LOOP TRANSIENT                     *************
********************************************************************************
*
* REFERENCE - ORIGINAL PROGRAM VERSION  AND DATA FORMAT IS DESCRIBED IN
*        " TURBOTRANS SCHEME FOR STEADY-STATE OR TRANSIENT PERFORMANCE
*          CALCULATIONS OF GAS TURBINES WITH OR WITHOUT CONTROL SYSTEM
*          - USER'S GUIDE " - PALMER AND YAN CHENG-ZHONG MARCH '82
*
*
*************              COUGUAR CONFIGURATION              *************
*
*
* INTAKE: COMPRESSOR :BLEED: COMBUSTION :TURBINE :BLEED: JET   :CONVERGE :
*       :            :     : CHAMBER    :        :     : PIPE  :NOZZLE    :
*1------2------------3-----3------------4--------5-----7------8---------9
*1      2            3     3            4        5     7      8         9
*1      2            3     3            4        5     7      8         9
*1      2            3  13 3            4        5 13  7      8         9
*.------2------------3--13-3------------4--------5-13--7------8---------9
*                      13                         13
*                      13------>-------->-------13
*
*
3--3--3--3      version3 update 9/9/86 to NOZCON,NOZDIV      3--3--3--3
4--4--4--4      version4 update 15/1/87 open-loop transient  4--4--4--4
*


* title
COUGUAR SINGLE-SPOOL TURBOJET ENGINE T.S PERFORMANCE////
* selectors (DP or OD) (SS or TS) (IM or SI) (KE or HY) (EP,SP or NP)
OD SS SI KE FP
* transient instructions here - none for SS
* transient-time step,final time,
* printout -time interval,initial time, trace index
0.025 15.875 0.125 0. 1.
* optional compressor map(s)   terminated by -1
* sequence number
1
* add COUGUAR map here
-1
* optional turbine map(s)      terminated by -1
-1
*--4--4--4 update
* optional control schedules   terminated by -1
* open loop transient - pseudo control to input
*        fuel flow versus time trace
* sequence number
1
* pseudo PLA versus time schedule
* 30 values   time
0. 1.00 2.00 3.0 3.5 4.0 4.25 4.5 4.75 5.0
5.25 5.5 5.75 6.0 6.25 6.5 6.75 7.0 7.25 7.5
7.75 8.0 8.5 9.0 9.5 10.0 11.0 12.0 14.0 15.875
* 30 values   pseudo PLA
39.2 39.2 39.2 39.2 39.2 39.2 39.2 39.2 39.2 39.2
44.3 48.4 49.8 52.0 53.9 54.4 55.4 57.0 59.3 60.2
60.5 63.0 64.0 64.5 65.8 67.3 67.9 69.3 69.5 69.5
```

```
*sequence number
2
* pseudo fuel flow versus PLA relationship
* 30 values pseudo PLA
1.   5.  10.  15.  20.  25.  30.  32.  34.  36.
38.  40.  42.  44.  46.  48.  50.  52.  54.  56.
58.  60.  62.  64.  66.  68.  70.  72.  74.  90.
* 30 values fuel flow
0.001 0.005 0.01 0.015 0.020 0.025 0.030 0.032 0.034 0.036
0.038 0.040 0.042 0.044 0.046 0.048 0.050 0.052 0.054 0.056
0.058 0.060 0.062 0.064 0.066 0.068 0.070 0.072 0.074 0.090
-1



*
* engine codewords
*
* brick name (6 letters)       : COMPRE       : compressor
* station vectors              : S 2-3        : SV(2),SV(4)
* brick data                   : D 5-12       : BD(5),etc
* engine vector results        : R101-102     : BD(101),etc
* variables                    : V1,2,5 W2,2,6 : BD(5),BD(6)
* label                        :             :
INTAKE S1-2 D1-4 R100
*               * R100 momentum drag (lbf or N)
COMPRE S2-3 D5-12 R101-102 V1,2,5 W2,2,6
*               * R101    COMWK compressor work (HP or W)
*               * R102    XN  rotor speed (rpm)
*               * V1,2,5  Z   see D(5)
*               * W2,2,6  PCN see D(6)
PREMAS S3,13,0 D13-16
BURNER S3-4 D17-23 R103
*               * R103    fuel fl w (lb/s or kg/s)
TURBIN S4-5 D24-31,101,32-34 V3,2,25
*               * V3,2,25 TF  see D(25)
MIXEES S5,13,7
DUCTER S7-8 D35-40 R104
*               * R104    fuel flow (lb/s or kg/s) (always)
*--3--3 update include two extra brick data items
NOZCON S8-9,1 D41-44 R105
*               * R105    gross thrust (lbf or N)
PERFOR S1,0,0 D45-46,105,100,103,0,0,0,0
*CODEND to terminate engine program proper
CODEND



* engine data title
TFDP DATA////
*K_REAL VALUE     *   ENGINE BRICK DATA BD(K)  ( K=1 to 150)(not > 150)

1 0.             *   INTAKE    ALT           (FT OR M)
2 0.0            *             ISA DEV        (K)
3 0.             *             FLT MACH NO
4 0.9945         *             P RECOVERY (0.0 TO 1.0) OR USAF (-1.)

5 0.9289         *   COMPRE    Z (R-Rc)/(Rs-Rc) R=PR OR 0.85 (-1.)
6 1.0            *             PCN (N/SRT(T))/STD   OR 1.0  (-1.)
7 3.91           *             Rdes  design Pressure Ratio
8 0.752          *             nis   des.isentropic eff.  (0.to 1.)
9 -1.            *             error sel.  (yes=1,no=0)
10 1.            *             compressor map no. (1.to 5.)
11 0.039079      *             lumped vol.  (FT3 OR M3) (-1.for SS)
12 48500.        *             XNDS rotor des. speed (rpm)
```

```
13 0.01           *   PREMAS   Lambda W - ? mass flow
14 0.             *            Delta W  -
15 1.0            *            Lambda P - ? total pressure
16 0.             *            Delta P  -

17 0.075616       *   BURNER   Delta P/Pin  loss/inlet
18 0.90           *            combustion eff. (0. to 1.)
19 -1.            *            fuelflow(lb/s or kg/s)(+or->calc or state T)
20 0.139422       *            lumped vol.  (ft3 or m3)  (-1.for SS)
21 1.             *            sel. fuel con.(<0 no: =0 step: >0 unit no.)
22 -1.            *            step fuelflow (kg/s or lbs/s)(-1.for no step)
23 0.15           *            safety factor (0.15 to 0.20) convergence

24 0.             *   TURBIN   AUXWK or POWER required (HP or W)
25 -1.            *            TF   (0. to 1.) or 0.8 for des.(-1.)
26 -1.            *            CN   (0. to 1.) or 0.6 for des.(-1.)
27 0.79           *            nis (0. to 1.)
28 -1.            *            PCN (0. to 1. POWER only)(-1. for COMP.)
29 1.             *            comp. no. (from 1. at low end)(0. for POWER)
30 1.             *            turbine map no. (1. to 5.)
31 -1.            *            power law index n (PCN**n)(-1. for const.)
32 0.01123        *            lumped vol. (ft3 or m3)
33 0.00612        *            PMI (N m s2 or lbf ft s2) (kg m2)
34 48500.         *            XNDS rotor des. speed (rpm)

35 0.             *   DUCTER   sel. reheat( 0. no : 1. later: 2. now )
36 0.0            *            Delta P/Pin loss/inlet
37 -1.            *            combustion eff. (0.to 1.)(if D(35)=1.or2.)
38 0.093795       *            lumped vol. (ft3 or m3)  (-1. for ss)
39 -1.            *            sel. fuel con.(<0. no:=0. step:>0 unit no.)
40 -1.            *            step fuelflow (or -1.0 no step)

*--3--3 update
41 -1.            *   NOZCON   sel. exit area (1. floats: -1. fixed)
42 0.096399       *            throat area (-1.area=DP : >0.value for ODP)
43 38.            *            noz. semi-angle ( 5. to 40. deg. inc.)
44 -1.            *            sel. area con. (<0. no : >0. unit no.)

45 -1.            *   PERFOR   POWER for power turbine or(-1.for jet/fan)
46 -1.            *            prop. eff.(0. to 1.) or(-1.for jet/fan)

* engine vector data lines terminated by -1
-1




*            station vector data lines (not > 200)
* station vector(i,j)  no.(i=1 to 25)   item no.(j=1.to 8) Value(real)
* intake mass flow
1 2 3.339
* burner outlet temp(must be stated if fuel flow value D(19) not given)
4 6 1183.
* ducter total outlet temp(if reheat is specified D(35))
* station vector data lines terminated by -1
-1




* Closed-Loop control unit codewords used to
* input fuel-flow time trace for open-loop transients

* control unit -data block
*           :- 11
*           : not > 25 control unit codewords
*           :CODEND
```

-11

```
MAIN FUEL CONTROL UNIT ////
COMAND  D1-3 R4-5  * transfers time,commands(fn  PLA) to control
CDTOED  D4,6-8     * transfers control output results to engine
CODEND

1 2.            *   COMAND  seq.no. of fuel v PLA  schedule
2 6.                       B.D. or S.V address of S.S start pt.
3 -1.                      -1 or S.V. address
6 1.            *   CDTOED  1 for fuelflow or area -1 others
7 22.                      engine (fuel)B.D. or S.V. address
8 -1.                      -1 or S.V. address
-1
* initial  Off-design data point values
2 2.7           *    INTAKE
19 0.0392       *    BURNER
* optional: other control unit program blocks
*           : terminated by -1
*           :- 1
* optional: other engine/station data blocks
*           :terminated by -2
*           :- 2
* optional: other program blocks (all above again)
*           : each terminated by 2,except last
*           : 2
* last or only program block terminated by -3
-1
-1
-3
```

APPENDIX B-2: Couguar Component Volumes and Spool Moment of Inertia

Spool Moment of Inertia 0.00612 lbf ft s^2

Component Volumes

    Compressor 0.0392 ft^3

    Combustion Chamber 0.1395 ft^3

    Turbine 0.01123 ft^3

    Jet pipe 0.09394 ft^3

APPENDIX B-3: Steady-state Input Datafile


```
COUGUAR SINGLE-SPOOL TURBOJET ENGINE S.S PERFORMANCE////
OD SS IM KE FP
1
.4124,.5608,.6804,.8022,.9072,.9691,1.0021,1.0454,1.0722,1.1134
1.0,.618,.500,1.275,.600,.680,1.370,.500,.835,1.360,.400,.825,
 1.380,.325,.800
1.0,.822,.450,1.785,.800,.780,1.865,.700,.855,1.870,.600,.855,
 1.870,.550,.840
1.0,1.010,.425,2.100,1.000,.780,2.300,0.960,.835,2.340,0.850,
 .845,2.340,0.755,.840
1.0,1.270,.400,2.600,1.250,.775,2.775,1.200,.810,2.810,1.100,
 .820,2.810,0.960,.825
1.0,1.560,.340,3.000,1.560,.725,3.300,1.500,.780,3.400,1.400,
 .805,3.465,1.265,.815
1.0,1.705,.300,3.300,1.700,.720,3.600,1.680,.760,3.775,1.600,
 .780,3.885,1.455,.810
1.0,1.810,.275,3.500,1.800,.700,3.800,1.755,.740,3.955,1.700,
 .765,4.080,1.545,.785
1.0,1.880,.250,3.700,1.870,.690,4.100,1.845,.735,4.260,1.770,
 .760,4.350,1.670,.775
1.0,1.975,.225,3.800,1.975,.660,4.200,1.960,.710,4.400,1.900,
 .740,4.570,1.770,.765
1.0,2.030,.200,3.900,2.025,.640,4.300,2.010,.690,4.700,1.955,
 .735,4.855,1.900,.750
-1
-1
-1
INTAKE S1-2 D1-4 R100
COMPRE S2-3 D5-12 R101-102 V1,2,5
PREMAS S3,13,3 D13-16
BURNER S3-4 D17-23 R103 V2,1,4,6
TURBIN S4-5 D24-31,101,32-34 V3,2,25
MIXEES S5,13,7
DUCTER S7-8 D35-40 R104
NOZCON S8-9,1 D41-44 R105
PERFOR S1,0,0 D45-46,105,100,103,0,0,0,0
CODEND

TFDP DATA////
1 0.0
2 0.0
3 0.0
4 0.9945
5 0.9289
6 1.0
7 3.91
8 0.752
9 -1.
10 1.
11 0.0392
12 48500.
13 0.01
14 0.0
15 1.0
16 0.0
17 0.075616
18 0.9000
19 -1.
20 0.1395
21 -1.
22 -1.
23 0.15
```

```
24 0.0
25 -1.
26 -1.
27 0.79
28 -1.
29 1.
30 1.
31 -1.
32 0.01123
33 0.00612
34 48500.
35 0.0
36 0.0
37 -1.
38 0.09394
39 -1.
40 -1.
41 -1.
42 0.096399
43 38.
44 -1.
45 -1.
46 -1.
-1
1 2 3.339
4 ( 1183.0
-1
6 1.01
-1
-1
6 1.00
-1
-1
6 0.98
-1
-1
6 0.96
-1
-1
6 0.94
-1
-1
6 0.92
-1
-1
6 0.90
-1
-1
6 0.88
-1
-1
6 0.86
-1
-1
6 0.84
-1
-1
6 0.82
-1
-1
6 0.80
-1
-1
6 0.78
-1
-1
```

```
6 0.76
-1
-1
6 0.74
-1
-1
6 0.72
-1
-1
6 0.70
-1
-1
6 0.68
-1
-1
6 0.66
-1
-1
6 0.64
-1
-1
6 0.62
-1
-1
-3
```

APPENDIX B-4: Open-loop Transient Input Datafile

COUGUAR SINGLE-SPOOL TURBOJET ENGINE T.S PERFORMANCE////
OD TS IM KE FP
0.025 15.875 0.125 0. 1.
1
.4124,.5608,.6804,.8022,.9072,.9691,1.0021,1.0454,1.0722,1.1134
1.0,.618,.500,1.275,.600,.680,1.370,.500,.835,1.380,.400,.825,
 1.380,.325,.800
1.0,.822,.450,1.785,.800,.780,1.865,.700,.855,1.870,.600,.855,
 1.870,.550,.840
1.0,1.010,.425,2.100,1.000,.780,2.300,0.960,.835,2.340,0.850,
 .845,2.340,0.755,.840
1.0,1.270,.400,2.600,1.250,.775,2.775,1.200,.810,2.810,1.100,
 .820,2.810,0.960,.825
1.0,1.560,.340,3.000,1.560,.725,3.300,1.500,.780,3.400,1.400,
 .805,3.465,1.265,.815
1.0,1.705,.300,3.300,1.700,.720,3.600,1.680,.760,3.775,1.600,
 .780,3.885,1.455,.810
1.0,1.810,.275,3.500,1.800,.700,3.800,1.755,.740,3.955,1.700,
 .765,4.080,1.545,.785
1.0,1.880,.250,3.700,1.870,.690,4.100,1.845,.735,4.260,1.770,
 .760,4.350,1.670,.775
1.0,1.975,.225,3.800,1.975,.660,4.200,1.960,.710,4.400,1.900,
 .740,4.570,1.770,.76ͻ
1.0,2.030,.200,3.900,2 025,.640,4.300,2.010,.690,4.700,1.955,
 .735,4.855,1.900,.750
-1
-1
1
0. 1.00 2.00 3.0 3.5 4.0 4.25 4.5 4.75 5.0
5.25 5.5 5.75 6.0 6.25 6.5 6.75 7.0 7.25 7.5
7.75 8.0 8.5 9.0 9.5 10.0 11.0 12.0 14.0 15.875
39.2 39.2 39.2 39.2 39.2 39.2 39.2 39.2 39.2 39.2
44.3 48.4 49.8 52.0 53.9 54.4 55.4 57.0 59.3 60.2
60.5 63.0 64.0 64.5 65.8 67.3 67.9 69.3 69.5 69.5
2
1.   5. 10. 15. 20. 25. 30. 32. 34. 36.
38. 40. 42. 44. 46. 48. 50. 52. 54. 56.
58. 60. 62. 64. 66. 68. 70. 72. 74. 90.
0.001 0.005 0.01 0.015 0.020 0.025 0.030 0.032 0.034 0.036
0.038 0.040 0.042 0.044 0.046 0.048 0.050 0.052 0.054 0.056
0.058 0.060 0.062 0.064 0.066 0.068 0.070 0.072 0.074 0.090
-1
INTAKE S1-2 D1-4 R100
COMPRE S2-3 D5-12 R101-102 V1,2,5 W2,2,6
PREMAS S3,13,3 D13-16
BURNER S3-4 D17-23 R103
TURBIN S4-5 D24-31,101,32-34 V3,2,25
MIXEES S5,13,7
DUCTER S7-8 D35-40 R104
NOZCON S8-9,1 D41-44 R105
PERFOR S1,0,0 D45-46,105,100,103,0,0,0,0
CODEND

TEDP DATA////
1 0.0
2 0.0
3 0.0
4 0.9945
5 0.9289
6 1.00
7 3.91
8 0.752

```
 9 -1.
10 1.
11 0.0392
12 48500.
13 0.01
14 0.0
15 1.0
16 0.0
17 0.075616
18 0.90
19 -1.
20 0.1395
21 1.
22 -1.
23 0.15
24 0.0
25 -1.
26 -1.
27 0.79
28 -1.
29 1.
30 1.
31 -1.
32 0.01123
33 0.00612
34 48500.
35 0.0
36 0.0
37 -1.
38 0.09394
39 -1.
40 -1.
41 -1.
42 0.096399
43 38.
44 -1.
45 -1.
46 -1.
-1
1 2 3.339
4 6 1183.0
-11
MAIN FUEL CONTROL UNIT ////
COMAND D1-3 R4-5
CDTOED D4,6-8
CODEND
1 2.
2 6.
3 -1.
6 1.
7 22.
8 -1.
-1
2 2.7
19 0.0392
-1
-1
-3
```

APPENDIX C–1: Difference between Simulated and Experimental Running Line

(Expressed as a % of the Parameter value at 100% N_c/N_{Des}

	Engine Parameter								
Operating Pt. $\dfrac{N_c}{N_{Des}}$ % of Des	MA_c	$\dfrac{P3}{P0}$	$\dfrac{T3}{T0}$	WF_c	$\dfrac{P4}{P0}$	$\dfrac{T4}{T0}$	$\dfrac{P5}{P0}$	$\dfrac{T5}{T0}$	FN_c
	lb/s			lb/s					lbf
100.0	−0.59	−0.78	−0.61	0.31	−1.4	1.31	−1.84	−0.89	−1.32
95.0	0	−0.26	−1.22	−1.24	−1.4	2.89	−1.23	−0.89	−0.92
90.0	0	−0.26	−1.22	1.24	−0.56	3.94	0.61	0	1.21
85.0	0.29	0	−0.61	1.08	−0.28	3.94	0.61	0.30	1.32
80.0	−0.59	−0.78	−1.83	−0.46	−1.12	4.20	0	0.89	0.29
75.0	−0.29	−0.52	−0.61	−0.93	−0.56	4.20	0.61	1.79	0.63
70.0	0	0.26	0	−1.85	0.28	3.67	0.61	1.79	1.26
65.0	0.59	1.04	0	−2.16	1.4	3.94	1.23	1.19	1.84

APPENDIX C-2: Steady-State Gains from simulated running line

$$(\Delta \text{Parameter}/ \Delta Wf_c)$$

N Range for Fuel Step % of Des.	Engine Parameter								
	$\dfrac{N_c}{N_{des}}$	MA_c	$\dfrac{P3}{P0}$	$\dfrac{T3}{T0}$	$\dfrac{P4}{P0}$	$\dfrac{T4}{T0}$	$\dfrac{P5}{P0}$	$\dfrac{T5}{T0}$	FN_c
95 – 100	568.	25.0	38.6	6.8	37.5	23.9	10.2	17.0	2955
90 – 95	746.	37.3	49.3	8.9	43.3	19.4	11.9	14.9	3313
85 – 90	833.	40.0	50.0	8.3	46.7	20.0	11.7	13.3	3366
80 – 85	877.	45.6	52.6	10.5	47.4	21.1	12.3	12.3	3316
75 – 80	1351.	54.1	56.7	10.8	51.4	18.9	10.8	5.4	3459
70 – 75	1250.	50.0	50.0	10.0	45.0	22.5	12.5	15.0	3100
65 – 70	1471.	50.0	47.1	11.8	38.2	23.5	8.8	14.7	2941

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An open-loop, transient, thermodynamic model of the single-spool Couguar turbojet has been developed for use in both fault diagnosis and engine control research work. The model is based on TURBOTRANS, a generic engine modelling computer program, and it has been calibrated against test cell measurements of the steady-state running line. The model provided good predictions of a series of accelerations and decelerations over the operating range of the turbojet. Estimates of the steady-state gains and time constants, across the speed range of the engine, are also p ented.

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